Fires in Silos

Edited by
Ulrich Krause

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Fires in Silos

Hazards, Prevention, and Fire Fighting

Edited by
Ulrich Krause

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Preface

This book is addressed first of all to engineers who work as plant designers or operators or in management in the process industries, in energy conversion, in recycling, in the woodworking industry or in the food industry where large amounts of flammable bulk materials are stored in silos. It is intended to provide a background of knowledge of the fire hazards in silo storage facilities together with recommendations for fire prevention and protection.

A second group which may be interested in this book are fire fighters. As all the experience gathered in some case studies of this book shows, fire fighting in large storage facilities is always a big challenge to those concerned. Large masses of flammable materials involved in the fire, huge emissions of heat, smoke and potentially harmful gases and awkward access to the fire sites lead to extensive, difficult, risky, time-consuming and costly fire fighting missions.

Therefore, the main focus should always be on preventing fires in silos. This can be achieved when plant operators are well aware of

- the hazards linked with the flammable materials they store or handle,
- the hazards resulting from processing itself, for example the appearance of explosible atmospheres and ignition sources,
- technical and operational measures which can reduce the probability of a fire or an explosion to occur or mitigate their consequences to protect people, equipment and the environment.

Finally, responsible authorities supervising storage facilities may be interested in this book as well to use it as a condensed knowledge base for a complex problem.

That is why the purpose of the present book is

- to raise awareness of the fire hazard in storage facilities and the eventually disastrous consequences of such fires including losses of life and economic bankruptcy,
- to transmit lessons learned in previous incidents,
- to spread the expertise gathered by the contributors of this book to those confronted with the problem.

However, it seems impossible to reduce the risk of a fire to zero. The present book attempts to summarize the state of the art of technical and administrative precau-

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tions to be taken, first of all to prevent incidents or – if they occur – to allow an effective fire fighting.

Most of the preventive and protective measures apply to storage of flammable bulk materials in facilities other than silos as well, for example heaps or free deposits or storage in bunkers.

The presentation of knowledge in this book is more on a technical than on a scientific level to ease readability. Mathematics has been reduced to an absolute minimum.

The board of authors of this book comprises fire investigators, researchers, fire consultants and providers of fire protection equipment. All authors have a long-term experience in the field. It is our strong desire that this book may help to prevent these specific kinds of events or at least to facilitate bringing them under control.

It is the strong wish of the editor to sincerely thank everybody who has contributed to this book. This includes the authors for providing their unique expertise and experience and the publisher, Wiley-VCH, for the professional treatment of the manuscript and for the patience with the editor when doing his part of the work and last but not least the editor's beloved family giving him the freedom and time for writing and editing.

Bergholz-Rehbrücke, Germany *Ulrich Krause*

1
Introduction

Ulrich Krause

1.1
Problem Description

In industry and transportation silos serve as containers for storing bulk materials or dusts. Volumes of silos range from a few cubic meters as supply silos in process chains to some thousand cubic meters for storing fuels, grain or sugar, for example. Recently, in Europe some coal storage silos have been erected storing up to 50 000 tons of coal.

Many silos are of cylindrical shape but there are also silos with rectangular cross section or those formed by the intermediate space between adjacent cylindrical silo cells. As will be explained below, silo size and shape affect fire appearance and fighting.

Silo batteries – an arrangement of up to 100 or more single silo cells on one site – offer storage capacities for dozens of thousands of tons of material.

About 80% of bulk materials are flammable, among them those which are stored in large masses like grain or other crops. Hence, in the case of a fire the release of an enormous amount of energy has to be expected, which endangers the static integrity of the structure and makes fire fighting extremely difficult. In addition, huge emissions of smoke and flue gases impede the access to the fire site and harm the environment.

Besides the fire itself the hazard of an explosion has to be taken into account when flammable bulk materials are stored in silos. Fine particles may be contained in the bulk material or are produced by abrasion during handling. When these fine particles are dispersed in air as may happen during filling or emptying the silo, eventually an explosive dust cloud is formed in the interior of the silo. If an ignition source of sufficient energy is then in place a dust explosion is likely to occur.

Another explosion hazard results from flammable gases. Under the action of a heat source many organic bulk materials undergo thermal decomposition (pyrolization) whereby flammable gases like carbon monoxide, methane, propane

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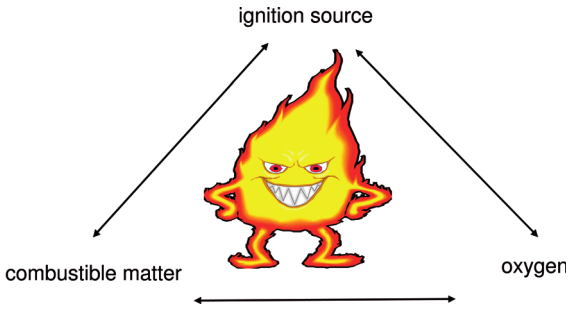

Figure 1.1 The fire triangle.

or hydrogen are produced. If these gases mix with air an explosible gas cloud may be generated.

To start a fire three pre-requisites are necessary: a flammable material has to be brought together with an oxidizer (in most cases the oxygen contained in the ambient air) and an ignition source has to act on the mixture. This relation is described by the well-known fire triangle, Figure 1.1.

In silos where flammable bulk materials are stored, the first two pre-requisites are present permanently. The reason why not all of these silos go up in flames is the absence of an effective ignition source. Ignition sources are characterized by their energy and their duration of action. Not every ignition source is able to ignite any flammable material or mixture. There is a strong relation between the efficiency of an ignition source and the ability of the material to act as a receptor of the ignition energy. The ignition sensitivity of a material depends on its chemical structure and on physical properties like particle size, porosity and moisture content.

The physical and chemical properties of materials which are relevant for the fire behavior will be described later in the present chapter. Chapter 2 deals with different mechanisms of ignition of solid materials in detail, among them self-ignition of bulk materials, which has been revealed to be the cause of a large number of silo fires in the past.

In a hazard analysis five different factors have to be considered:

- hazards connected to the bulk material handled,
- hazards connected to the process equipment,
- hazards connected to the mode of operation and maintenance,
- the velocity of the fire spread,
- the losses expected in the case of a fire or an explosion.

The assessment of these factors leads to a concept for prevention of and protection against fires and explosions. Both technical and operational measures are possible; in many applications different measures of these two types are combined. Risk assessment is described in detail in Chapter 3, especially the analysis of hazardous properties of bulk materials. How to take appropriate preventive and protective

measures to minimize the hazard of a fire or an explosion in silos is explained in Chapter 4. Some technical solutions for fire detection, alarming and subsequent fire suppression which are currently available on the market are presented in Chapter 5.

Chapter 6 contains a number of case studies of silo fires from which many valuable lessons could be learned. In the cases mentioned it turned out that there are some significant differences to, for example, fires in buildings which require different fire fighting strategies and expert knowledge.

Chapter 7 is intended to give some guidance for fire fighting in different situations fire fighters may encounter when called to a silo fire site. This is demonstrated using a further case study, however focused more on fire fighting than on the causes of the fire and the chain of events.

In Chapter 8 special precautions are highlighted for the case when inerting is the measure of choice for fire extinction.

Chapter 9 introduces briefly computational methods for the prediction of self-ignition and fire propagation scenarios considering a computational model of the real silo configuration as an example of advanced methods for fire hazard assessment.

1.2 Influence of Material Properties on Fire

Bulk materials are characterized by a number of physical and chemical properties. Some of these properties have strong relevance for ignition sensitivity and fire spread. There are different mechanisms of how bulk materials react in a fire. Firstly, organic materials when exposed to heat may decompose and release gases some of which are combustible themselves and burn in a gas-phase reaction. Secondly, the solid material itself or the solid residues of the decomposition reaction burn by oxidation at the surface of the solid particles.

It is obvious that at least the reaction rate of the combustion step largely depends on the free surface area the particles offer to the oxygen molecules to be absorbed. Hence, the volume fraction of the voids within the bulk good is of importance for the fire behavior. Oxygen penetrates into or between the voids by diffusion or if the voids are large enough by convection. The characteristic length scale of this type of mass transfer is the free path length between the voids, which depends on the particle diameter.

Furthermore, for most bulk goods each individual particle has pores which allow oxygen to penetrate into the particle and then to react with the solid. The pores may be of such a size that free motion of the oxygen molecules is no longer possible. This type of diffusion is called Knudsen diffusion. The characteristic length in this case is the pore diameter.

1.2.1 Particle Size Distribution, Particle Shape and Internal Surface Area

Particles in an arbitrary deposit of bulk material may have different sizes and shapes.

Fractions of freshly mined coal for example range from up to several tens of centimeters to a few millimeters depending on the brittleness of the coal and on the mining method. In addition, significant amounts of dust particles with diameters in the range of micrometers may be present, for example due to the excavation procedure or due to abrasion during transportation. For such a material the particle diameters cover several orders of magnitude.

Other products like grain consist of particles within a comparatively narrow range of particle sizes of a few millimeters. However, a small but non-negligible portion of fine dust usually exists.

The traditional method to measure particle diameters is sieving. Mostly vibratory sieves are used, where the particles fall successively through a cascade of sieves of decreasing mesh sizes. By weighing the masses of particles remaining on the different sieves the particle size fractions can be determined within the range given by the mesh width of the different sieves. As a result of interpolation between the discrete mesh widths one obtains a curve as plotted in Figure 1.2.

An example of such a vibratory sieve is shown in Figure 1.3.

A more recent way of particle analysis is the laser diffraction method. In this method the particles are dispersed either in a liquid or in a gas flow and a laser beam passes through the suspension. The interaction of the laser beam with the surface of a particle causes a bending of the light waves. This effect depends on the curvature of the particle surface and can be measured by a detector.

Both methods work best when the particles are of spherical shape. In this case the particle size is defined unambiguously by the particle diameter. Normally bulk goods will, however, not be of spherical shape. This is the main source of error in particle size analysis. Figure 1.4 shows electron microscope scans of dust particles of three different Chinese black coals and a German lignite coal.

A key quantity to characterize the susceptibility of a bulk good to react is the internal surface area. This quantity strongly corresponds to the particle porosity

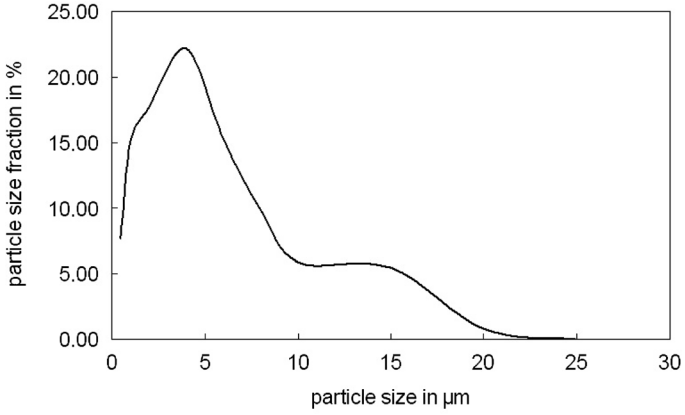

Figure 1.2 Result of the particle analysis of a fine dust.

Figure 1.3 Vibratory sieve for particle size analysis of particulate matter (Courtesy of Retsch GmbH).

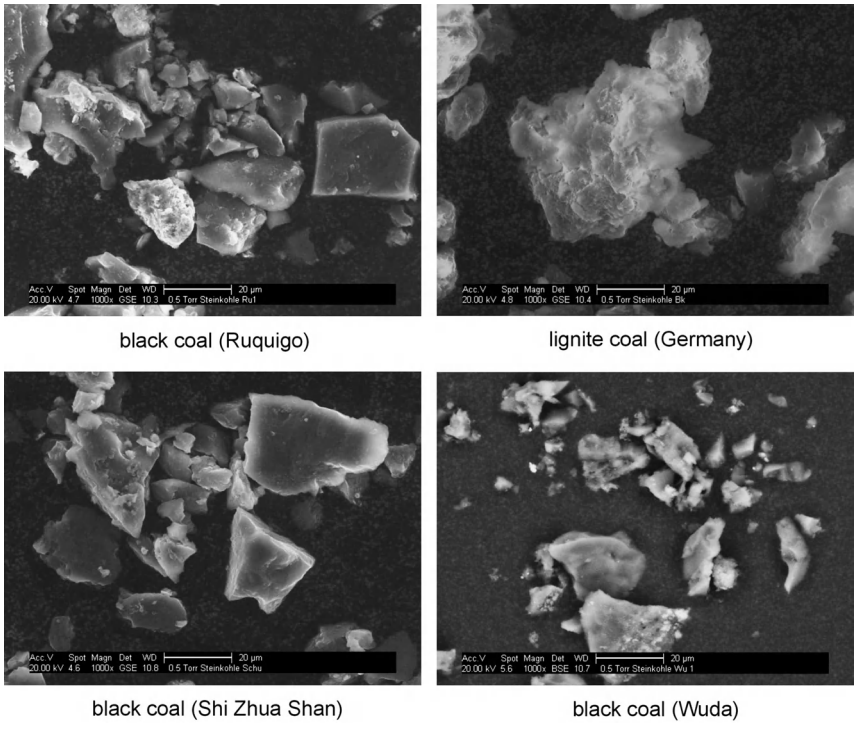

Figure 1.4 Electron microscope scans of cut-to-pieces particulate material.

described in Section 1.2.3, below. The internal surface area of a particle is the totality of all surfaces the particle offers to an adsorbate including those of each individual pore.

In powder technology it is more common to work with the specific surface area, which is the internal surface area divided by the mass of the particle. The unit of the specific surface area is therefore m^2/g.

In general, a particle is the more reactive the larger its specific surface area. The specific surface area can be measured by the BET method, where BET stands for the developers of this method: Brunauer, Emerett and Teller. In this method after evacuating the sample of particles one measures the amount of a gas which can be adsorbed in a monomolecular layer on the particle surface. Mostly nitrogen at a temperature slightly above its boiling point (77 K) is used as an adsorbate.

1.2.2
Bulk Porosity and Bulk Density

The bulk porosity is the ratio of the volume of the voids in an accumulation of bulk material to the entire volume of this accumulation. The voids are filled with gas so that the porosity may be described according to Equation (1.1)

$$\varepsilon = \frac{V_g}{V_g + V_s} \tag{1.1}$$

where V_g is the volume taken up by the gas phase and V_s the volume occupied by the solid particles. The latter one is the sum of the volumes of individual particles.

For bulk goods loosely heaped up porosities have to be expected in a range between about 0.3 and 0.8 depending on the kind of material. Compaction of the heap reduces the porosity.

The bulk density – sometimes also called the apparent density – is closely related to the porosity. It is defined as

$$\rho_b = \varepsilon \cdot \rho_g + (1-\varepsilon) \cdot \rho_s \tag{1.2}$$

where ρ_g is the density of the gas filling the voids and ρ_s is the density of the solid particles forming the heap. The bulk density of a bulk good can be measured more easily than the bulk porosity. A widely accepted method is described in the standard ISO 171 [1].

The porosity can then be calculated from the bulk density, the gas density and the particle density

$$\varepsilon = \frac{\rho_s - \rho_b}{\rho_s - \rho_g} \approx \frac{\rho_s - \rho_b}{\rho_s} \tag{1.3}$$

Provided that the gas pressure, temperature and composition are known, the gas density can be obtained from the equation of state for a perfect gas

$$\rho_g = \frac{p \cdot M}{R \cdot T} \tag{1.4}$$

with p as the pressure and T as the temperature on the Kelvin scale. M is the molecular mass of the gas and R is the universal gas constant.

The particle density can be measured as described in Section 1.2.4, below.

1.2.3 Porosity of Individual Particles

Solid particles of coal, wood, grain, cotton and many other products have internal pores. The pore diameters range from a few micrometers (macropores) to a few nanometers (micropores). Some of these pores are open to the particle surface; others may be completely embedded in the solid material (blind pores). Figure 1.5 shows a sketch of the pore structure of a solid particle.

For the behavior of the particle in a fire only the open pores are of interest since they allow oxygen to be adsorbed at the surface of the particle.

Particle porosity can be measured using special equipment. Different porosimeters are available to measure the sizes of macropores, mesopores or micropores. The sizes of macropores are measured by injecting liquid mercury into the pores of particles which previously have been evacuated. As there is a correlation between the pore size and the injection pressure, a stepwise increase of the injection pressure gives the pore size distribution of the solid.

The sizes of mesopores and micropores are measured using gas adsorption techniques. In this case nitrogen or carbon dioxide is injected into the pores instead of mercury.

The particle porosity strongly influences the ignitability and the burnout rate of solid particles. The higher the porosity the larger the surface the particle offers to oxygen molecules to react. Therefore, particles with high porosity ignite more readily than those with low porosity. In addition, the burnout takes place much faster when the porosity is higher.

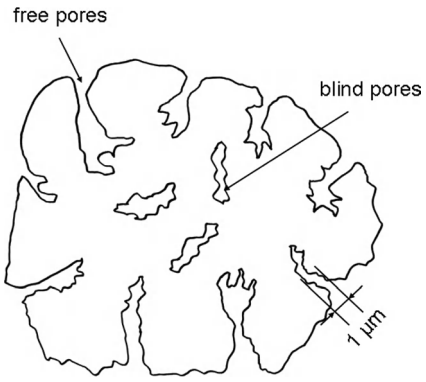

Figure 1.5 Pore structure of a solid particle.

1.2.4 Particle Density

The particle density is the mass of the particle divided by the volume of the particle. This quantity can be measured using a so-called pycnometer. In the simplest case a sample of particles of which the mass is known is immersed in a liquid and the extrusion of the volume of the liquid is measured. For very precise measurements and if the porosity of the particles is high, a gaseous fluid, say helium, is used instead of a liquid and the pores are evacuated before the measurement.

1.2.5 Humidity

Humidity plays a key role in the susceptibility of flammable bulk goods to ignite; however, different and partly counteracting effects have to be considered. Experiments by Krause and Schmidt [2] have shown that samples of wood chips or crushed lignite coal with volumes between 6 and 13 L could not be ignited by an embedded heated coil when the mass fraction of water was 40% or higher.

Below this content of water smoldering fires could be initiated within the bulk goods. The propagation of these smoldering fires was of course delayed compared to dry samples due to the evaporation of the water.

Hence, there seems to be some kind of limit of the water content above which fire propagation is not possible because the heat provided by an ignition source or produced by a beginning exothermic reaction is completely absorbed by the water. Below this limit the influence of the water on ignition of bulk goods may be either impedimental or promotive. The impedimental effect is simply the absorption of heat from the ignition source or from a beginning exothermic reaction to heat up and evaporate the water.

A promotive effect of water on the ignition of bulk goods may be observed, for example, when freshly harvested plants are stored; for example, hay, alfalfa, forage and so on. Some silo fires happened because moist goods were stored. A case study describing this effect is contained in Chapter 6 of this book. Therefore, in the case of organic material it is important to reject material with a humidity higher than 16% in mass for storage.

As experience shows, at a mass fraction of water above 16% in mass fermentation starts within the stored material raising the temperature to a level as high as 70 °C. Together with the oxygen contained in the air filling the void volumes of the stored material the elevated temperature forms a favorable starting condition for self-ignition. More details about the mechanism of self-ignition will be given in Chapter 2.

Another promotive effect of water occurs when comparatively dry bulk goods are wetted (without being soaked through). When the water is adsorbed at the surface of the solid particles the heat of adsorption is released. This leads to a temperature rise in the heap of the bulk goods which may be a pre-condition for a self-ignition. Indeed, practitioners from the mining industry have reported that for example coal deposits when exposed to rain after a longer period of dry weather start to smolder.

A similar effect can be observed when the humidity of the air striking above the surface of the deposit is increased. Here, in addition to the heat of adsorption, the heat of condensation is also released and contributes to a temperature increase within the bulk material. Experimental evidence of these phenomena has been gained by Lohrer [3].

A rough but simple method to measure the humidity of a bulk good is drying a sample of the material in a vacuum dryer. The mass fraction of water is simply the difference between the initial mass of the sample and the mass after drying. The drying temperature has to be chosen in such a way that thermal decomposition of the material does not occur. The drying is finished when between two successive weighings no alterations of the mass are observed.

A more precise method to measure the humidity of solid materials is titration. A detailed description of this method is given for example in [4].

1.3 Chemical Properties of Bulk Goods

1.3.1 Chemical Structure

Besides the physical properties mentioned in Section 1.2 the behavior of bulk goods in a fire is also influenced by their chemical properties. The main fire (and explosion) hazard results from the ability of these materials to react with oxygen connected with the release of heat. There are different laboratory tests to assess the flammability of materials, which are described in Chapter 3.

Most of the bulk goods stored in silos and revealed to be flammable are of organic nature. This also includes coal which originates from organic matter, but which is sometimes considered to be a mineral. The chemical structure of coal is not completely understood until now and in addition may vary depending on the origin. However, according to Wang *et al.* [5] there is some evidence that coal contains so-called functional groups originating from carbohydrates and these functional groups mainly influence the behavior during oxidation.

Other exceptions are, for example, some metal powders like aluminum, brass or others, carbon black which is nearly 100% carbon and activated carbon which usually consists of more than 95% carbon.

A chemical species which has bonded the maximum possible number of oxygen atoms cannot burn. An example for such a material is sand, which mainly consists of silicon dioxide. A silicon atom has four free electrons in its outer shell. Each oxygen atom can bond two of them such that the silicon dioxide molecule is stable. The same applies to a carbon atom, which also has four free electrons. Therefore, carbon dioxide is also non-combustible. Both sand and carbon dioxide are well known as extinguishing agents.

In contrast to this, in carbon monoxide two free electrons remain and hence a molecule of carbon monoxide can react with an oxygen atom to form carbon dioxide.

It is well known that carbon monoxide is an explosible gas (and in addition a very toxic one).

More complex molecules contain so-called functional groups. Functional groups are fragments of other molecules which are bonded to the first one. For example, 2-butanone (methyl ethyl ketone), which is a product of wood fires, has an ethyl group which is a fragment of an ethane molecule. The bondings of functional groups are sometimes comparatively weak and therefore easy to destroy. During such a process heat is released, which leads to a temperature rise in the material.

1.3.2 Heat of Formation and Calorific Value

Any molecule of a chemical species is composed of different chemical elements. The elements are linked to each other by a chemical bond. Some chemical reactions consume external energy, for example in the form of heat, to synthesize a molecule (endothermic reaction). This energy is then stored in the molecule as heat of formation. The total heat of formation of the products is higher than that of the reactants.

When such a molecule is broken up by some other chemical reaction the heat of formation is released again and increases the temperature of the reactive system (exothermic reaction).

Other molecules evolve spontaneously when the reactants are activated by a small portion of energy (the so-called activation energy). Spontaneous reactions are always connected with a release of energy. This means that the total heat of formation of the products is always lower than the total heat of formation of the reactants. The difference is the heat of reaction.

The unit of the heat of formation is J/mol. Chemical elements and molecules of monatomic gases by definition have a heat of formation of zero. Since during the formation of some molecules out of their elements heat is released, these molecules have a negative heat of formation. For example, the heat of formation of water at standard conditions (atmospheric pressure, 25 °C temperature) is −286 J/mol, that of carbon monoxide is −111 J/mol and that of carbon dioxide is −394 J/mol. If carbon monoxide reacts with oxygen to form carbon dioxide the heat of reaction is $\Delta H_R =$ 111 J/mol − (−394 J/mol) = 283 J/mol.

It needs no explanation that fires are always dominated by exothermic reactions (despite some intermediate reactions in the flame that may be endothermic). A quantity that describes how much heat can be released when a certain amount of reactant is burnt is the gross calorific value. The gross calorific value is the ratio of the heat energy released during combustion of a fuel to its mass. For example, the quality of fossil fuels can be ranked according to their gross calorific value.

Some flammable solids like coal, wood, cellulose, grain and others contain a fraction of hydrogen. During combustion the hydrogen reacts with oxygen and forms water vapor. The latent heat of the water vapor reduces the energy which can be extracted from the combustion. Therefore, the net calorific value is the gross calorific value diminished by the latent heat of vaporization.

In fire safety often the fire load is used to estimate the heat release of a fire. This is the gross calorific value multiplied with the total mass of material stored and divided by the ground area on which the material is stored. For storage of bulk materials, however, it is more appropriate to use the volume of the storage facility instead of the ground area.

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2
Ignition Sources

Vytenis Babrauskas and Ulrich Krause

2.1
Introduction

A silo is a cylindrical tower used for storing agricultural or granular materials. These materials are most commonly agricultural products, but can also be industrial powders. Thus, the nature of the material must be considered in order to understand potential ignitions. In general, there may be three types of substances liable to ignition:

(1) flammable or combustible gases,
(2) dust clouds,
(3) the settled layer of granular material.

Gases are, of course, not intentionally stored in silos, but may be generated due to a chemical reaction (e.g., fermentation) of the stored solids. Similarly, dust clouds are an inadvertent effect of silo operation and are created due to pouring of material. Ignition sources, in turn, are divided into two broad classes:

(a) external, localized sources of heat,
(b) self-heating.

We consider in this chapter first the external ignition sources and then the self-heating process as an ignition source. It should be noted that the external/self-heating dichotomy, while simple to express, is not necessarily strictly obeyed in practice. Some problems are basically self-heating, but involve a portion of the space which is at a higher temperature. Even though this is, in principle, a localized source of heat, these types of problems are still treated as self-heating problems.

2.2
External Ignition Sources

An external ignition source can be any localized source of energy which suffices to ignite the relevant substance. The question of whether a particular source of energy

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will suffice to ignite a given substance is not easy to answer, however. In only a very few cases is it sufficient to consider simply the amount of energy available, that is, the minimum ignition energy (MIE). Instead, it is usually essential to know how the energy is being delivered, not just its totality. The "how," in turn, can be expressed as four different characteristics of an ignition source which can determine the ignition process:

- the temperature,
- the total energy supplied,
- the rate at which it is supplied, or the time period over which it is delivered,
- the area over which it is delivered.

But this formalism, while conceptually useful, is not sufficient to help solve quantitative problems today. In the recently published Ignition Handbook [1], it proved necessary to consider the individual characteristics of ignition sources for each different class of ignition source; consequently, ignition sources were grouped into broad functional categories:

(a) high ambient temperatures (what is "high" depends on the substance, of course),
(b) hot solids, liquids or gases (contact with),
(c) shock, impact, pressure or vibration (i.e., mechanical forces),
(d) flames or remote burning objects,
(e) electric current, static electricity, electromagnetic waves and particulate radiation,
(f) light energy, lenses and mirrors,
(g) aerodynamic heating.

Not all of these categories, of course, are of equal importance – (a), (b), (d) and (e) are pervasively important, while the other three occur only in specialized situations. Furthermore, category (a) is generally considered in the context of self-heating, not as a source of localized, external heating. Thus, in practice, only (b), (d) and (e) must be considered.

2.2.1 Hot Solids, Liquids or Gases

For this category, as applied to silos, only hot solids generally need to be considered, since ignition by a hot liquid or a hot, non-flaming gas would be extremely rare. Hot solids can act as an ignition source for gases, dust clouds and settled layers. In practice, a hot solid might arise as "tramp metal," due to failure of some metal part of machinery or due to electrical heating. For the ignition of gases, a fair bit is known on an empirical basis, although quantitative applications of theory are less satisfactory.

2.2.1.1 Ignition of Gases by Hot Solids

Experiments have determined that very high temperatures are needed to ignite a gas by means of a hot solid. In 1816, Sir Humphry Davy [2] observed that plunging an iron bar "at the highest degree of red heat and at the common degree of white heat" into a firedamp (mostly methane) –air mixture did not ignite the mixture. The hot-solid

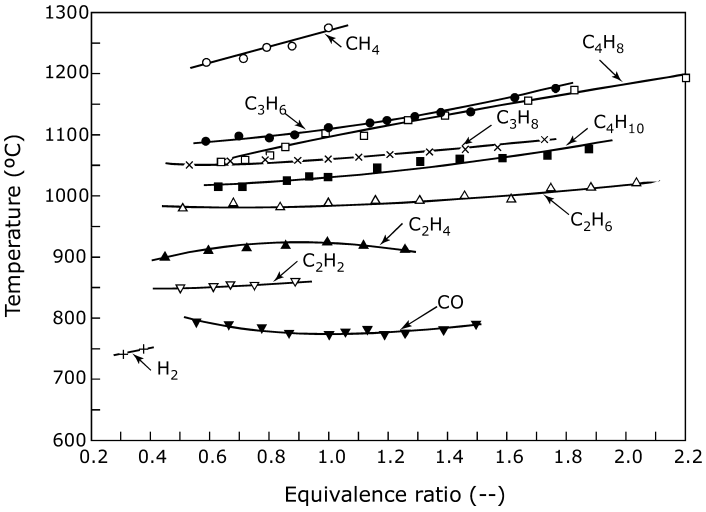

Figure 2.1 Temperatures needed to ignite various gas–air mixtures using a 1 mm Nichrome wire (*Reprinted from Ignition Handbook with permission of publishers*).

temperature needed will normally be much higher than the AIT (auto-ignition temperature) of the particular fuel–oxidizer mixture. The reason is that AIT testing is conducted in a vessel where the mixture is uniformly heated. But, with an isolated hot surface, while a gas volume directly next to the heated surface does heat up to a high temperature, convective effects quickly sweep it out of that area, where it is cooled down. Figure 2.1 shows some results on temperatures required for a 1 mm diameter Nichrome wire to ignite various gas–air mixtures. Methane, which has an AIT of 640 °C, requires roughly twice as high a temperature to ignite as a Nichrome wire.

But, experiments have shown that the area of the hot surface is crucially important, not just its temperature. This is shown in Figure 2.2 for several gases; Figure 2.3 shows results for methane, which behaves somewhat differently from other gases. Theories have been offered to predict these trends, but the agreement with experimental data has not been very good, except for selected data sets. Thus, the problem remains empirical in nature.

Somewhat different considerations apply to the case of ignition by *fused wires*, that is, a wire which has an electric current passed through it sufficient to actually melt the wire. Mixtures of methane–air can readily be ignited [3] by a fused wire of modest size, for example less than 0.4 mm (Table 2.1).

2.2.1.2 Ignition of Dust Clouds by Hot Solids

Dust clouds are ignitable by hot surfaces, but either very large areas or very high temperatures are needed. Not much data exists on this subject, with results from Zeeuwen [4] and Eckhoff [5] being shown in Figure 2.4. Similar trends are seen, but values differ substantially (note that wheat flour was tested by both authors). The differences are presumably due to experimental conditions, but details that might explain this have not been published. Gibson and Schofield [6] compared AIT data for

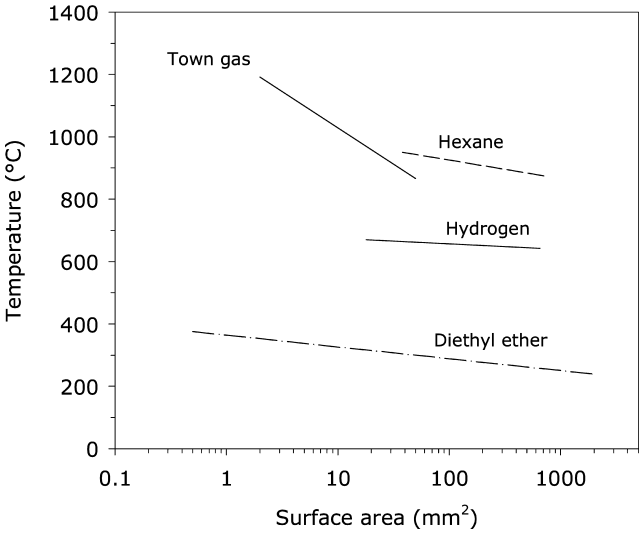

Figure 2.2 Effect of hot surface area on ignition of several fuel gas–air mixtures (*Reprinted from Ignition Handbook with permission of publishers*).

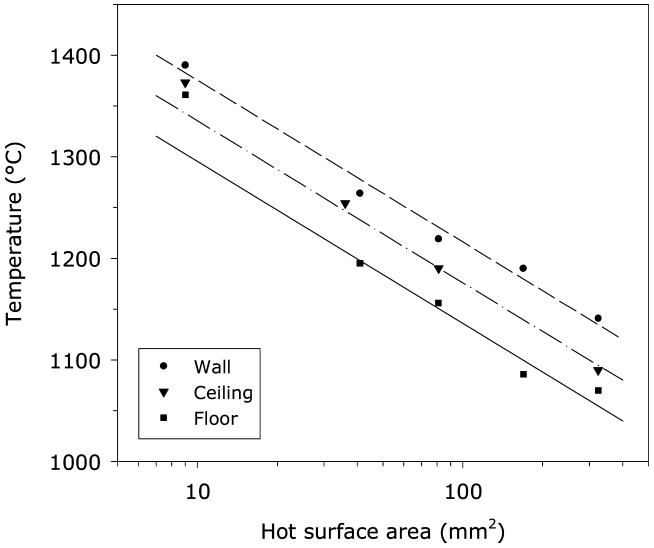

Figure 2.3 Effect of hot surface area and orientation on ignition of mixtures of 6% methane in air (*Reprinted from Ignition Handbook with permission of publishers*).

a large number of dusts with data obtained from a test using a 0.27 mm coiled wire as the hot surface. Their findings indicate that the temperature of the 0.27 mm hot wire must be about 400 °C greater than the AIT of the dust cloud for an ignition to be expected.

Table 2.1 Zborovszky's results on the ignition of 8.3% methane in air by heated wires.

Wire	Diameter (mm)	Current needed for ignition (A)	Must fuse for ignition to occur
Copper (100 mm long)	0.254	[a]	
	0.327	[a]	
	0.381	46	yes
	0.508	32	yes
	0.635	80	yes
Beryllium/copper (80 mm long)	0.178	4.25	yes
	0.38	11	no
Tungsten (11 mm long)	0.178	4.5	yes
	0.178	3.5	no
Tungsten (80 mm long)	0.178	4.25	yes
	0.38	9–12	no

[a]Wire fused, but no ignitions obtained.

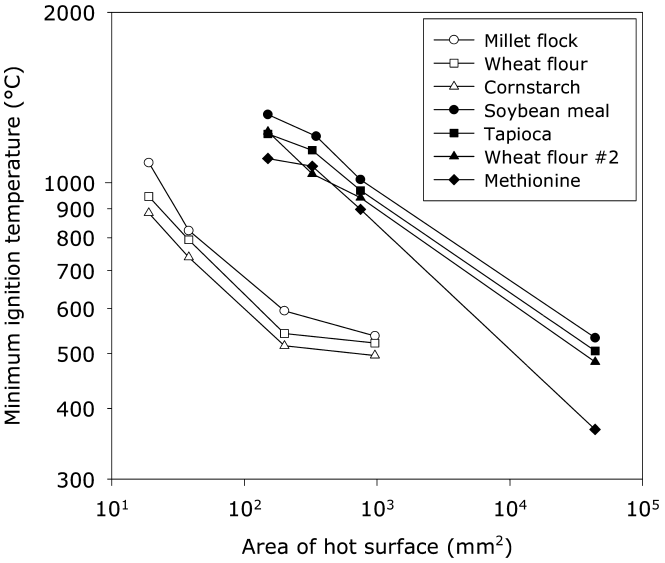

Figure 2.4 Relation between area of hot surface and minimum temperature needed for ignition (solid symbols: Zeeuwen; hollow symbols: Eckhoff) (*Reprinted from Ignition Handbook with permission of publishers*).

A *mechanical spark* is a type of hot solid, since it is simply an incandescent particle that has been created by grinding, filing, impact or similar activities. Sparks from steel against steel or steel against concrete will not ignite dust clouds. But, ignition is possible in the case of an especially susceptible metal, such as titanium. In addition,

experimental studies [7] indicate that a dust cloud is liable to ignition from mechanical sparks only if

(1) the dust cloud has an MIE <10 mJ,
(2) the auto-ignition temperature of the dust cloud is <500 °C.

In this context, the values of MIE refer to the use of an inductive circuit, while AIT measurements are taken in a BAM furnace.

There is one additional ignition source which must be considered for dust clouds and that is the *glowing nest*, which is a small mass of granular material that is actively smoldering. Eckhoff [5] surveyed a number of studies on the topic. While universally applicable guidance did not emerge, some salient conclusions were

- Nests of 700 °C falling through dust clouds were non-incendive during flight, but caused some ignitions when landing at the bottom. Nest weights of at least 15 g were required for those ignitions to occur.
- Nests having a temperature ≥900 °C and a surface area ≥75 cm^2 were able to ignite dust clouds that had AIT values of ≤600 °C, as tested in the BAM oven [8].
- If nests disintegrate in free fall, they may be able to create a fireball which then ignites the dust cloud. But, nests of this type cannot be conveyed for any significant distance, because they would disintegrate in transport.

More recently, Gummer and Lunn [9] reviewed the literature and conducted tests of their own. They concluded that smoldering nests that fall down through a dust cloud will not ignite clouds with AIT > 400 °C, as measured in a Godbert–Greenwald furnace [10]. A smoldering dust layer will not ignite clouds with AIT > 340 °C, while a flaming dust layer will not ignite those rare clouds that have AIT > 600–800 °C.

2.2.1.3 Ignition of Solids by Hot Solids

The typical problem of ignition of a solid by a hot solid is an event such as welding slag dropping onto a wooden board. This is normally not an ignition source in silos, where the ignitable solids are generally in the form of granular material, not large single pieces of solid material. A hot sphere embedded into a granular material is a classical problem for self-heating substances; thus, this is considered later in this section.

2.2.2 Flames or Remote Burning Objects

A flame can be a competent ignition source for gases, dust clouds, liquids and solids. The conditions will generally have to be very rare or unusual for an open flame *not* to ignite a flammable gas mixture or a dust cloud (Figure 2.5).

A small flame requires a more concerted exposure for typical solids to be ignited. Unfortunately, there is no theory available which can predict the response of a solid to the application of a small flame. This is, in part, due to the fact that the heat transfer situation is innately three dimensional and difficult to model. Furthermore, many solids respond to a flame by shrinking, melting or warping; thus, there is a coupled

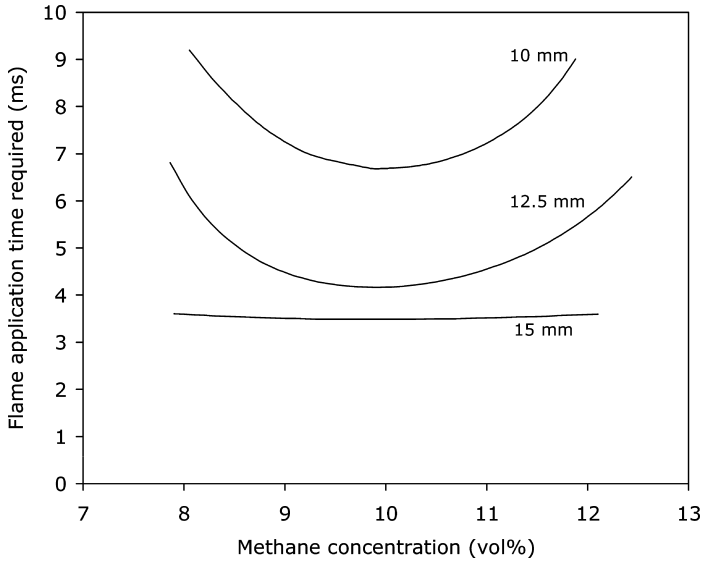

Figure 2.5 Ignition of methane–air mixtures by pilot flames of various lengths (*Reprinted from Ignition Handbook with permission of publishers*).

thermostructural problem which would have to be solved. In practice, resistance of solids to small-flame ignition is determined by testing. There are hundreds of small-flame tests which have been promulgated by various standards associations or governmental entities. Of these, probably the most widely used standard is UL 94 [11]. This, in fact, is not a single test but a series of tests of varying challenge. Most commonly used are the 94-V procedures, which involve a small specimen vertically oriented and subjected to a flame at the bottom of the specimen. These tests are especially common in the plastics industry, but the results should not be interpreted as having a fundamental meaningfulness – changing the test conditions slightly is likely to lead to a significantly different outcome. However, if a material fails the "V-0" classification, it can reasonably be concluded that it is very easily ignitable by small flames.

Dust clouds, liquids and solids can also be ignited without a direct application of a flame, but by heat flux from a burning object which is remote from the target fuel. This is an important fire mechanism in some industries, for example petrochemical processing, but is not one of the primary ignition scenarios needing to be considered for silos. A large fire near a silo, however, should be viewed as an extreme hazard and ignition in such cases must obviously be considered to be possible.

2.2.3
Electric Current, Static Electricity, Electromagnetic Waves and Particulate Radiation

For application to silos, electric current and static electricity must be considered as potential ignition sources. Other related phenomena (direct heating by

electromagnetic fields, particulate radiation, etc.) are very rare and unlikely to be encountered in practice.

2.2.3.1 Electric Current

In any industry or application where electric current is used, the possibility of a fire from this source of energy must be considered. Electric current can be a competent ignition source for substances in any state, gas, dust cloud, liquid or solid. The two most important mechanisms by which ignition can occur are (a) arcs or sparks; and (b) poor connection or other condition which leads to localized heating of electrical conductors. An electric arc going through the air raises the temperature to at least 6500 K (see Figure 2.6). All ignitable substances have ignition temperatures that are much lower. This observation, however, does not imply that an electric arc is 100% assured of igniting a particular combustible. Surprisingly, the details of this have not been studied, but two factors can be considered at least qualitatively. (1) The ignition temperature of a substance refers to the temperature of the substance itself, not of nearby air. If a massive object is introduced into a low-power electric arc, the arc may simply be quenched. (2) Thin or light-density solids are unlikely to quench the arc, but they may be vaporized and fail to ignite.

A *spark* is different from an *arc*, in that an electric spark is a transient discharge, while an arc is a continuous discharge. Thus, an arc can be assured of igniting a flammable gas mixture, while an electric spark can be of such low energy content that

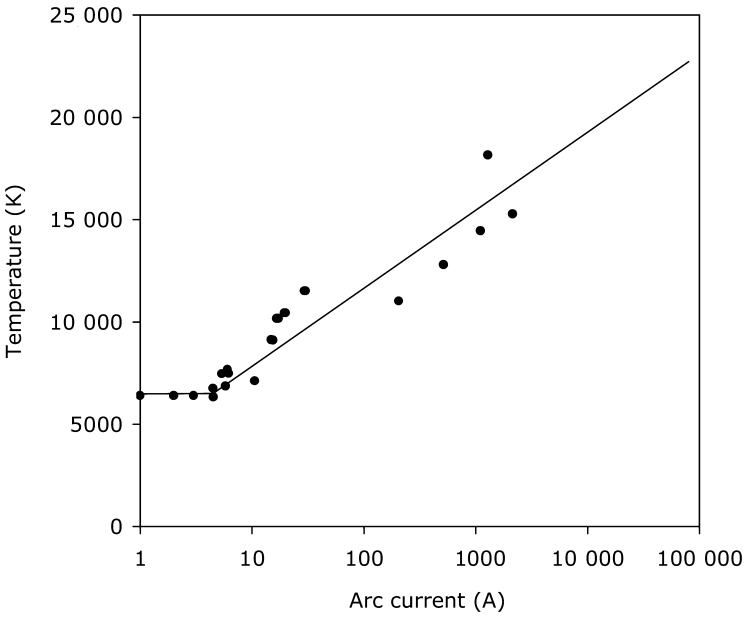

Figure 2.6 Temperature of an electric arc, as a function of the arc current (*Reprinted from Ignition Handbook with permission of publishers*).

Table 2.2 MIE values for selected gases and dust clouds.

Substance	MIE (mJ)
Acetylene/air	0.017
Hydrogen/air	0.017
Propane/air	0.26
Methane/air	0.30
Nylon dust	20–30
Wheat starch dust	25–60
Grain dust	30
Cornstarch dust	30–60
Grass seed dust	60–260
Polyethylene dust	70

it fails to cause ignition. The MIE values needed to ignite flammable gas mixtures are very low, however, and while they are higher for dust clouds, they are still low. Consequently, the possibility that the MIE would *not* be attained is often remote. Table 2.2 provides some typical MIE values for common gases and dusts. Note that these very small numbers are tabulated in *milli*joules.

Electric arcs or sparks occur both due to intentional operation (the contacts of switches, relays, etc.) and due to failures. Similarly, localized heating of electrical conductors can be intentional or due to a fault. Intentional heating includes devices such as electric lamps and electric heaters. These are commonly operated at white-hot temperatures. Electric heaters, of course, should not be used in environments where a flammable atmosphere exists. Electric lamps are a known cause of fire in some agricultural operations. This can include failures or breakage, or simply the accidental burial of an electric hand lamp in a pile of combustible material. Localized heating due to an electrical fault can create some very high temperatures. Oxidation of copper connections can create Cu_2O and the melting point of Cu_2O is 1230 °C; thus, temperatures in excess of the 1085 °C melting point of copper can occur, and these have been experimentally measured [12]. Electrical faults leading to localized heating are most commonly due to poor connections. These include screw connections, crimped connections and other forms of mechanical attachment. With any of these, insufficient tightening or corrosion or oxidation of the surfaces may initiate heating. Once initiated, heating can be a progressive failure, since heat may loosen the mechanical tension or increase corrosion or oxidation.

2.2.3.2 **Static Electricity**

Static electricity can lead to ignition due to accumulation of charge and subsequent discharge, which may be sufficient to cause breakdown of air or other insulating medium. The types of discharges involved are classified as

(1) spark,
(2) corona discharge,
(3) brush discharge,

(4) powder heap discharge,
(5) propagating brush discharge (Lichtenberg discharge),
(6) lightning-like discharge.

A normal *spark discharge* occurs through the air separating two electrodes when the electric field reaches a value of approximately 3 MV m^{-1}. Thus, for a gap distance d, the voltage V required is $3d$, where V is in megavolts and d is in meters. It is not sufficient, however, for ignition that a spark should occur, even if the energy delivered is in excess of the MIE for the flammable atmosphere where this event it taking place. If the gap is very small, thermal losses will be sufficient that a flame kernel cannot propagate and keep growing in the mixture. Losses are largely determined by electrode spacing, which must exceed the quenching distance for the particular fuel–oxidizer mixture. The latter is an experimentally determined variable, which may be roughly on the order of 2 mm. If 2 mm is the quenching distance, then the voltage required will be on the order of 6 kV.

A *corona discharge* is a slow, diffuse discharge that originates at a metallic electrode and branches out in a diffuse manner into space or towards poorly conducting surfaces. A corona discharge requires an electrode that has a needle-like point, typically less than 5 mm diameter. Corona discharges have the lowest energy of the electrostatic discharge types. The maximum energy normally realizable from a corona discharge – not much over 0.01 mJ – would theoretically suffice to ignite only the most ignitable of gases, such as H_2. Under some conditions, laboratory experiments have demonstrated that flammable-gas mixtures can be ignited; however, the conditions required have been extreme – in no case, however, will a corona discharge ignite dust clouds. Corona discharges are often used in processes and machinery as a safety measure for lowering charge accumulation.

When a grounded conductor is brought into an electric field that is near its dielectric breakdown strength, a gas discharge can occur in the form of a *brush discharge*. The discharge is able to occur because of electric field distortion introduced by the electrode, which locally raises the field above its breakdown value. The name comes from the brush-like shape of the discharge. A brush discharge is similar to a corona discharge in being a low-energy, one-electrode discharge, but whereas a corona discharge requires a needle-like electrode, a brush discharge occurs when electrodes have a radius of 5–50 mm. A brush discharge is a low-energy discharge and experimental studies indicate that a minimum voltage of about 20–25 kV is needed; furthermore, it is considered that discharges at less than about 60 kV are limited to certain laboratory experiments and are unlikely to occur in industrial accidents [13]. Even though about 3.6 mJ can be delivered in a brush discharge [14] and there are dust clouds that have an MIE $\approx$ 1 mJ, most studies have concluded that brush discharges will not ignite dust clouds [15], provided that the cloud is not a hybrid dust–gas mixture. A brush discharge has been shown to be capable of igniting dust clouds in certain highly unusual experiments [16].

A *powder heap discharge* can occur in some cases; when rapidly filling a silo with a powder, a much higher charge can build up in the settled powder than was present in the air through which the material moved. A discharge can then take place, made

possible when a growing volume of powder is aggregated such that, as the powder is compacted, its charge likewise becomes compacted if the powder is insulating and charge cannot be dissipated. Glor [17] computed certain theoretical limits to this form of the discharge. It turns out that a minimum particle size of about 0.1 mm is needed for a powder heap discharge to occur, but the majority of the actual incidents have involved polymeric resin particles in the 1–10 mm range. Early recommendations used to state that up to 10 mJ can be delivered in a single discharge step, but Glor [18] argued that discharges as large as 1000 mJ may be anticipated for large particles flowing into a large silo, although Britton [19] considered that Glor's test methodology was not realistic. A minimum product feed rate is also needed for a powder heap discharge to occur. This has been estimated at 3000–5000 kg h^{-1} for 3 mm particles, rising to 25 000–30 000 kg h^{-1} for 0.8 mm particles [21]. Powders having a resistivity of less than $10^{10}\,\Omega$ m are conservatively judged to not be susceptible to explosions from powder heap discharges [18]; powders which have caused explosions have had resistivities $>10^{12}\,\Omega$ m.

A very vigorous *propagating brush discharge* can occur under certain conditions when a charged insulator is in direct contact with a grounded conductor. A propagating brush discharge can ignite most flammable mixtures, including dust clouds, since up to about 1000 mJ can be delivered in this type of discharge. Circumstances leading to a propagating brush discharge can include [20, 21].

- conveying an insulating powder at high velocity through plastic pipes or bins that are grounded on their exterior,
- loading of insulating powders into large, non-conductive silos,
- operating at high velocities conveyor belts that have metallized outer surfaces and an insulating core,
- repeated collisions of dust particles on an insulating surface atop a grounded layer.

The final type of electrostatic discharge is the *lightning-like discharge*. It has been speculated that these might be able to occur in silos, but no evidence has thus far emerged that would confirm these speculations [22]. If they do exist, then they would be very energetic discharges and capable of igniting both gases and dust clouds. Since the existence of this particular form of discharge has not been demonstrated for silos, obviously it cannot be answered under which circumstances it might be produced.

2.3 Self-Heating

If a solid material ignites due to self-heating, there is no external ignition source. Instead, the ignition takes place because the material is undergoing exothermic chemical reactions and these heat it up in bulk. The simplest classical problem involves quickly assembling a disaggregated amount of the material into a single pile, with the material originally being at the same temperature as the environment in which it sits. In practice, the distinction between self-heating ignition and ignition due to external sources is not rigid because many varieties of self-heating problems

involve a hot surface; thus, there exists a localized area where increased energy is available. For common granular solids, the problem is still treated as a self-heating problem because (initially, at least) the chemical reactions are taking place internally within the material, not as a flame on the outside.

In addition to granular solids, gases and liquids can also be susceptible to self-heating ignition. For gases, this is the conventional auto-ignition problem, where ignition occurs because the substance is uniformly at a high temperature. Liquids undergoing self-heating, however, will normally not be encountered in connection with silos.

For self-heating to be possible, the substance must be capable of undergoing an exothermic reaction. In the case of solids, this usually requires that the material be porous or granular, since significant self-heating is usually not possible if reactions can only occur at the outside surface. In addition, the substance must be capable of smoldering. If raising the temperature causes a powder or granular substance to melt instead of smolder, then generally spontaneous combustion due to self-heating will be precluded.

For spontaneous combustion to occur, several events must take place in sequence:

(1) the material must exhibit self-heating,
(2) self-heating must reach a runaway, or critical, condition, that is, the reaction must rapidly accelerate so that a high temperature is reached,
(3) the runaway self-heating must start sustained smoldering,
(4) the sustained smoldering must reach the outside surface of the material and possibly erupt into flaming.

Materials which have undergone significant self-heating but have not exhibited spontaneous combustion will show a charred mass within the interior, but will not show smoldering or flaming on the exterior.

For most substances capable of spontaneous combustion, oxygen from the air is needed for chemical reactions to take place. Consequently, sealing the volume of the material or inerting it (e.g., with nitrogen) will normally stop the self-heating process. In general, it can be assumed that essentially all agricultural products and foodstuffs and most other organic substances which are in granular form can undergo self-heating.

A good introduction to the theory and mathematics of solving self-heating problems is given in the SFPE Handbook [23], while an extensive presentation is given in the Ignition Handbook [1]. The theory, however, is too specialized to be given here, and persons needing to work it should consult one of the two above references. In simplest terms, all self-heating theories express a balance between heat generation due to chemical reactions and heat losses due to cooling. The latter most commonly is represented by convective cooling along the outside periphery of the volume that is undergoing self-heating. Because heat generation is proportional to the volume and heat losses are proportional to the surface area, the problem has an intrinsic size dependence – the larger the pile of material the more readily it will go into thermal runaway. Thus, the larger the pile, the lower must be the ambient temperature in order to avoid the potential of spontaneous combustion, as illustrated in Figure 2.7.

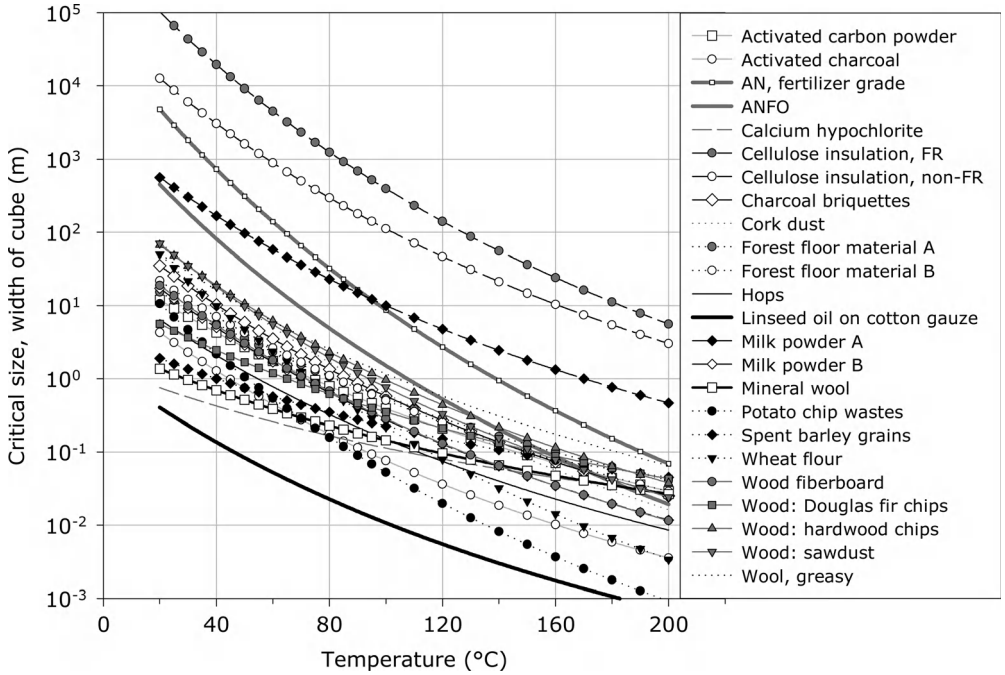

Figure 2.7 Relationship between size and critical ambient temperature estimated for various substances by applying a theoretical relationship to small-scale laboratory test results (*Reprinted from Ignition Handbook with permission of publishers*).

In general, testing is required to quantify the size/temperature relation for any given substance. This testing is most reliable if done in the actual size, or at least in intermediate size. Bench-scale testing procedures are also available. Ones that are based on using thermal analysis data (e.g., DSC – differential scanning calorimetry) are liable to produce exceedingly unreliable data, despite the existence of various prediction methods published by ASTM and other standards organizations. There are many reasons for this, but of largest concern is that real substances may show multiple, parallel reactions and these are either not detected with thermal analysis type methods or else cannot be successfully treated even if they are identified. An example of how a material can show this difficulty has been published [24].

More reliable is the oven-basket test method developed by the Fire Research Station [25]. With this technique, wire-basket cubes of various sizes, typically in the range 25–300 mm, are used, along with an oven which has good temperature stability and control. The critical temperature is found for a number of basket sizes and, using this data and a theoretical analysis, predictions are made for the real-scale commodity. This method still has the limitation that, because of the relatively small sizes involved, critical temperatures are usually above 100 °C, while the real situation may involve normal ambient temperature of 20 °C or so. This means that if the substance has a moisture component, the oven tests will be run with the

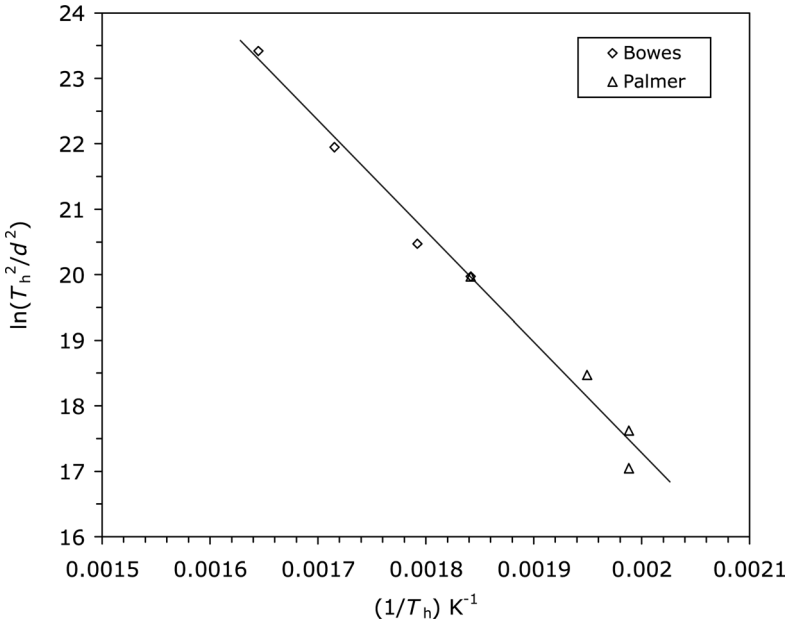

Figure 2.8 Hot plate results of sawdust testing by two authors plotted according to a simple correlation (*Reprinted from Ignition Handbook with permission of publishers*).

specimen fully desiccated, while in the real situation moisture movements may play a major role. For example, the self-heating of bagasse has been shown to be dominated by the moisture component [26], so testing at above 100 °C would not give correct results.

In industries dealing with dusts and powders, it is very common to use hot plate test methods such as ASTM E 2021 [27], EN 50281-1-2 [28] or IEC 61241-2-1 [29]. These are simple to use but, as pointed out by Ohlemiller and Rogers [30], their predictions should be considered, at best, only semiquantitative. Figure 2.8 shows some example results for sawdust, as plotted according to a procedure which is intended to linearize the data, with T_h = hot plate temperature (K) and d = layer thickness (m). Industrial testing, however, is often even simpler than this and is based on using only a single layer thickness and obtaining the critical temperature for that thickness. Such results are then used in a categorical context, that is, a determination is simply made whether the critical temperature is, or is not, above some specified value. Obviously, such a strategy must be considered useful only for very rough screening purposes.

Self-heating of hay in silos is a long-known problem and, indeed, the word "silo" originally referred solely to a device for producing silage from stored hay. There has been some quite extensive research on the self-heating of hay, but most of it has been done in the context of hay in haystacks, rather than in silos. The main difference is that, when stored in silos specifically for the purpose of creating silage, an airtight condition is approximated, which is not the case for haystacks. The problem of

self-heating in hay was of such practical importance that as early as 1907 an entire book on the topic of self-heating of hay was published in Germany [31].

It is considered that the self-heating of hay generally progresses through three stages. In the first stage, the biological respiration of the plant material still continues and provides heat. In the second stage, fungi and bacteria can flourish, and these provide additional heating. Their action can be complicated since one of the effects of microbial decomposition of carbohydrates is the production of water, thus changing the moisture balance of the material. The final stage occurs after temperatures have risen enough to kill off micro-organisms. This involves the chemical oxidation reaction of the hay itself. Firth and Stuckey [32] applied these general principles of self-heating of hay to understanding of fires in silage.

When stored in silos, hay is optimally at 50–65% moisture content when put into a top-unloading silo and 45–55% for a bottom-unloading silo [33]. Self-heating is most likely to occur for somewhat dry hay, at about 30%; this may occur due to air leaking in through cracks in walls or doors. Very dry hay at around 20% will not self-heat due to lack of conditions suitable to microbial heating. A fire is made more likely if the hay is improperly packed so that it is not tight against the silo walls – this condition makes it easier for air to reach the interior of the silage. Spontaneous combustion is less likely in silos constructed to be oxygen-limiting, compared to ones with more significant air leakage.

Grasses of all kinds, even those not suitable for fodder, generally show similar behavior to hay. Rothbaum [34] reported tests for the self-heating propensity of Moroccan esparto grass. For all types of agricultural substances, there is the possibility that relatively minor concentrations of inorganic materials may affect the self-heating process [35] and that self-heating may be promoted when plants have been grown in a chalky or limestone soil [36].

2.4
Physical Characteristics of Self-Ignition Processes and Smoldering Fire Propagation

Ulrich Krause

The process of self-ignition as described in Section 2.3 is characterized by physical effects which – if observed – can be used as typical signs of a fire and of the state in which it is developing.

The characteristic range of temperature for a self-ignition process turning into a smoldering fire is from 150 to 400 °C.

A range of temperature from 250 to 500 °C indicates a propagating smoldering fire with the temperature being the higher the more oxygen is available for combustion. Experience shows that during the propagation of a reaction front through a bulk material stored in a silo the concentration of oxygen is not sufficient to exceed a reaction temperature of 500 °C or, respectively, to turn from smoldering into glowing. Glowing occurs when the reaction front breaks through to the outer surface of the stored mass or when by any means the stored material is penetrated to the depth of the reaction front.

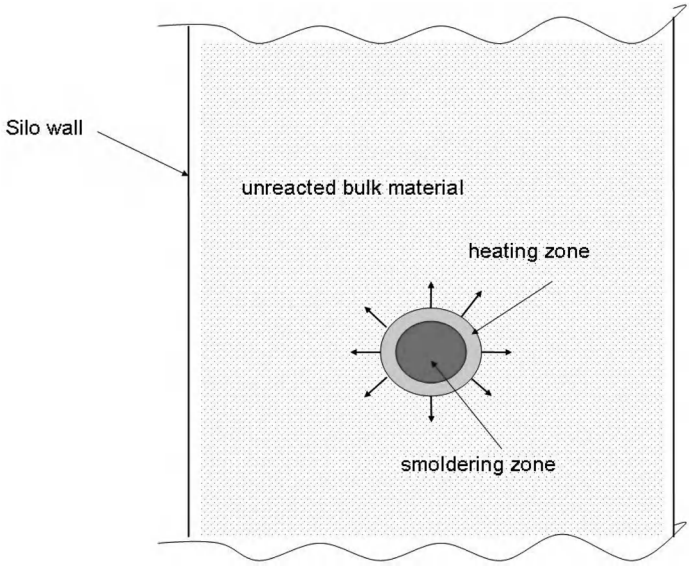

Figure 2.9 Propagation of a hot spot through bulk material in a silo.

A smoldering fire can roughly be assumed as the propagation of a reaction front detaching from a "hot spot" where the increase of temperature occurs first. The front propagates into the virgin bulk material, as depicted in Figure 2.9.

The reaction consumes the oxygen which is contained in the air filling the voids between the particles. The higher the temperature, the more oxygen is consumed because the reaction rate grows with the temperature exponentially.

When the oxygen within the vicinity of the reaction front is consumed, the reaction can only propagate after fresh oxygen is transported there from more distant regions within the bulk material or from outside. Hence, the reaction rate is controlled by the flux rate of oxygen through the bulk material. Depending on the pathways available for a gas to migrate through the bulk material and on the external pressure the predominant mechanism for gas transportation may be either convection or diffusion. The free path length between adjacent particles is a measure for the porosity of the bulk; see also Section 1.2.2.

In a smoldering fire the described reaction mechanism is sustained until the reaction front breaks through to the surface of the stored bulk material.

A further indication of a smoldering fire propagating through a porous bulk material is an increased concentration of gaseous reaction products like carbon monoxide, carbon dioxide and water vapor. Depending on the elemental composition of the bulk material other gases may be released as well in a smoldering fire like, for example, sulfur dioxide or hydrogen sulphide. In fact, some smoldering fires in silos were detected first by somebody noticing a "strange odor" indicating the release of sulfur hydrogen.

The transition from self-heating to self-ignition is always accompanied by an enhanced generation of gas. An elevated level of volume fractions of CO, CO_2, H_2O or

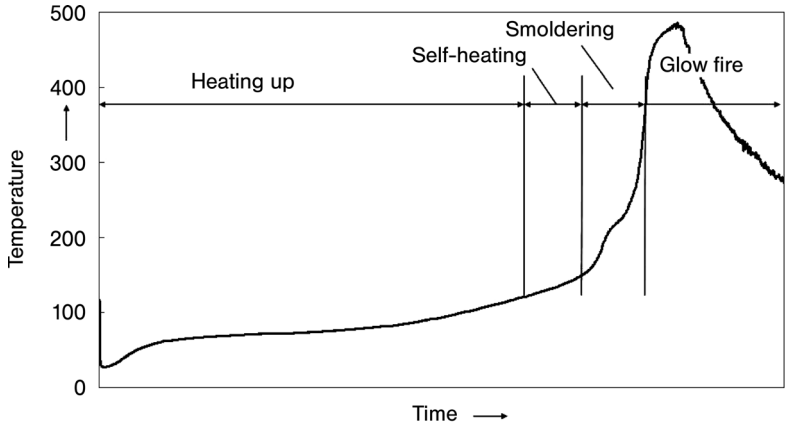

Figure 2.10 Stages of a fire in bulk material triggered by self-ignition.

CH_4, for example, at the top of the silo cell indicates the existence of a reaction kernel within the bulk material.

The occurrence of water vapor at the transition stage from self-heating to self-ignition has two reasons. Firstly, physisorbed water (moisture) is released under the action of heat and migrates as vapor to the silo top. Secondly, if the stored material is organic, water is an oxidation product. Hence, an increased humidity of the gas sampled at the silo top indicates an ongoing smoldering.

The interpretation of the measured ratio of CO and CO_2 is not unambiguous. Under the condition of reduced oxygen, as occurs in the vicinity of the reaction zone, the reaction equilibrium is shifted to the direction of CO.

When the reaction front breaks through to the surface the smoldering turns into a glow fire. The reaction temperature in a glow fire is in the range 500–800 °C and thus is higher than for smoldering. It is, however, well known for the reaction of carbon with oxygen that at temperatures higher than 700 °C the output of CO increases gradually with temperature (Bouduard reaction). Figure 2.10 shows an illustration of the development of a fire through bulk material.

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3
Fire Risk Assessment

Javier García Torrent and Enrique Querol

3.1
Introduction

Any industrial installation processing combustible solids should be analyzed not only from the point of view of fire prevention but also from prevention of explosive atmospheres; thus, the so-called ATEX directives [1, 2] must be applied. This applies also to storage facilities like silos and the peripheral installations like conveyors, sieving machines, bucket elevators and so on.

One of the requirements of these regulations is the explosion risk analysis, which includes the risk identification, where the knowledge of the materials' safety characteristics is of capital importance. Unfortunately, the materials' safety data sheets, MSDS, in most cases do not contain adequate information about the important parameters for explosion risk analysis and data must be searched for or experimentally obtained. It is necessary to know what are the significant parameters and their applications to different hazard situations.

Among the ignition sources that must be analyzed, the European standard EN 1127-1 [3] refers to the presence of exothermic reactions, including self-ignition of dusts. Fires arising from self-heating of solid products have been reported from a wide range of industries in manufacturing processes, storage and transportation.

Self-heating is an oxidation phenomenon that produces heat and, whenever it is greater than the heat dissipated to the environment, increases the material temperature until combustion is reached. The knowledge of this self-combustion process is of great technical value, but nowadays there is not a unique standardized method generally accepted yet. Although several techniques have been proved among different research studies, no one is fully accepted [4, 5].

In this chapter different experimental methods and techniques for measuring those characteristics are presented.

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3.2
Experimental Techniques

The different characteristics of powder, granular, fibrous and dusty solid products can be grouped as a function of the nature of the parameters

- ignition sensitivity,
- explosion severity,
- thermal susceptibility,
- thermal stability,
- classification of solid dangerous goods.

Let us analyze each of these groups.

3.2.1
Ignition Sensitivity

In this group characteristics related to easiness of ignition by different sources (thermal sources and electrostatic discharges) are included (Figure 3.1)

3.2.1.1 Minimum Ignition Temperature (MIT)

It is the lowest temperature at which the dust ignition process starts. It determines whether a present heat source is able to initiate the process or not. The corresponding test can be done either with the dust forming a cloud (MIT-c) or deposited in a layer (MIT-l) [6]. The test device used for MIT-c consists of a vertical cylinder, the inside of which is electrically heated at a certain temperature, where the dispersion is produced. The appearance of flames makes ignition evident at the fixed temperature (Figure 3.2). Some data can be found referred to a horizontal testing device called a BAM oven; this generally produces lower temperature values.

The test apparatus used for MIT-l is a metallic plate whose temperature can be varied, upon which the dust is deposited forming a 5 mm thick layer. If the temperature within the layer exceeds the plate temperature, it is understood that ignition has been produced, even if no flame is seen (Figure 3.2).

The layer ignition temperature depends on the layer depth; the deeper the layer, the lower the temperature. Also, the time needed to reach ignition increases with the layer depth. For layers not exceeding 75 mm, MIT can be measured using the apparatus and procedure described in EN 50281-2-1 that applies in that standard for depths of 5 mm (Figure 3.4).

Figure 3.1 Characteristic parameters for ignition sensitivity.

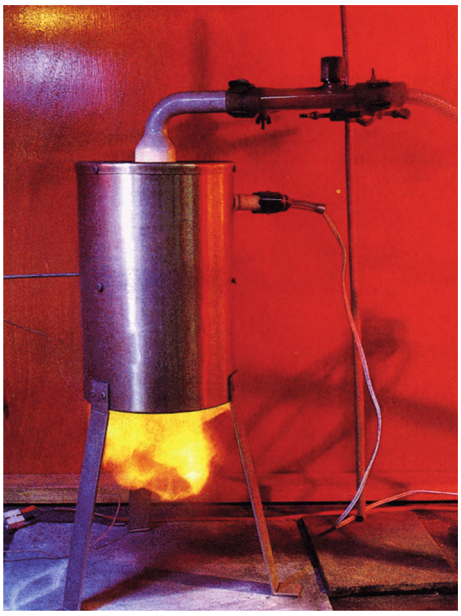

Figure 3.2 MIT_{layer} test.

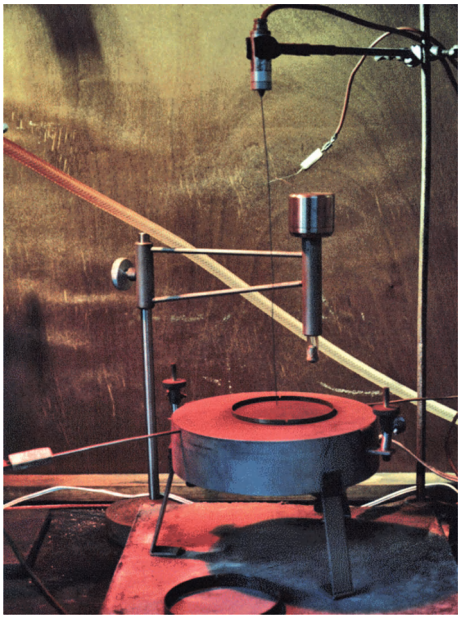

Figure 3.3 MIT_{cloud} test.

Figure 3.4 MIT_{layer} test for thick layers.

Minimum layer ignition temperatures of some products for different layer heights of 5 mm, 10 mm, 15 mm, 20 mm, 30 mm, 50 mm and 75 mm were determined as part of the experimental testing carried out for a European R + D project [7]. Results showed that estimates of the layer ignition temperatures for thick layers can adequately be calculated by extrapolating from layer ignition temperatures of thinner layers by using the procedure described in EN 50281-2-1 (Figure 3.5).

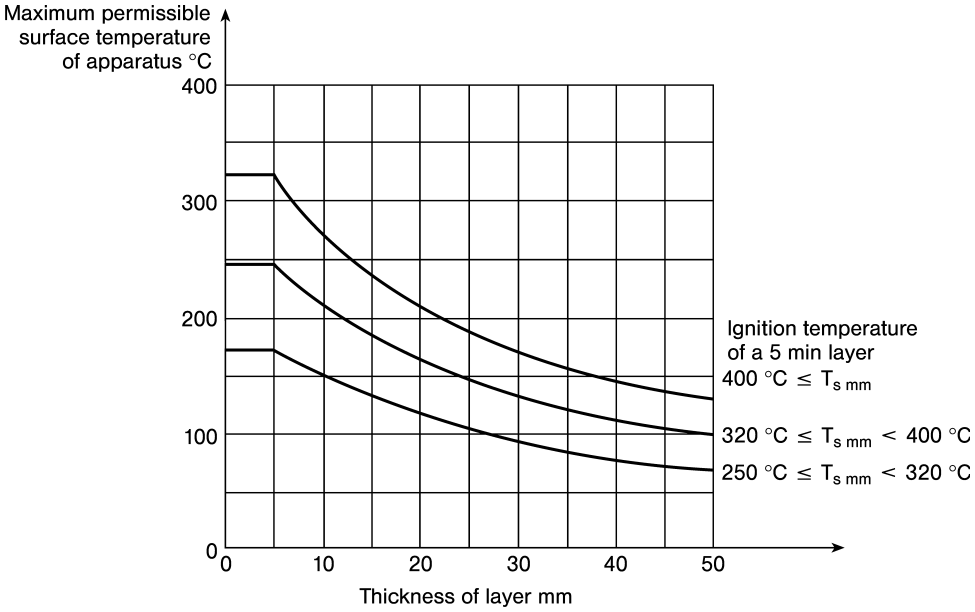

Figure 3.5 Permitted surface temperature vs. layer thickness.

3.2.1.2 Minimum Explosible Concentration (Lower Explosion Limit (MEC/LEL))

There is a range of dust cloud concentrations within which the dust–air mixture is explosive. The lower limit is the MEC, also known as the LEL. The traditional test procedure was based on the so-called Hartmann tube, but nowadays it has been replaced by ignition tests in a standard explosion vessel [8].

3.2.1.3 Minimum Ignition Energy (MIE)

It is the lowest energy value of a high-voltage capacitor discharge required to ignite the most suitable dust–air mixture. Energy (in joules) is calculated from the equation $E = {}^1/_2 CU^2$, where C is the total capacity of the discharge circuit and U is the applied voltage.

The minimum ignition energy MIE lies between the lowest energy value (E_2) at which ignition occurred and the maximum energy (E_1) at which in at least 10 successive experiments no ignition was observed. It is possible to calculate a unique statistic value, E_s, by estimating the probability of ignition.

3.2.2 Explosion Severity

When ignition takes place without confinement, its effects dissipate in the surroundings. However, during an explosion in a closed vessel very high pressures can be developed producing devastating effects (Figure 3.6).

Under test conditions, the mechanical effects of the dust–air mixture explosions can be measured and registered. That occurs when the explosion takes place under controlled conditions in a testing vessel which can withstand the explosion effects. Some parameters can be measured (Figure 3.7).

3.2.2.1 Explosion Pressure (P_{max})

During an explosion in a test vessel, the pressure changes form a curve (see Figure 3.8). When this explosion curve is obtained over a wide range of dust

Figure 3.6 Destruction produced after an explosion in a silo installation.

Figure 3.7 Characteristic parameters for explosion severity.

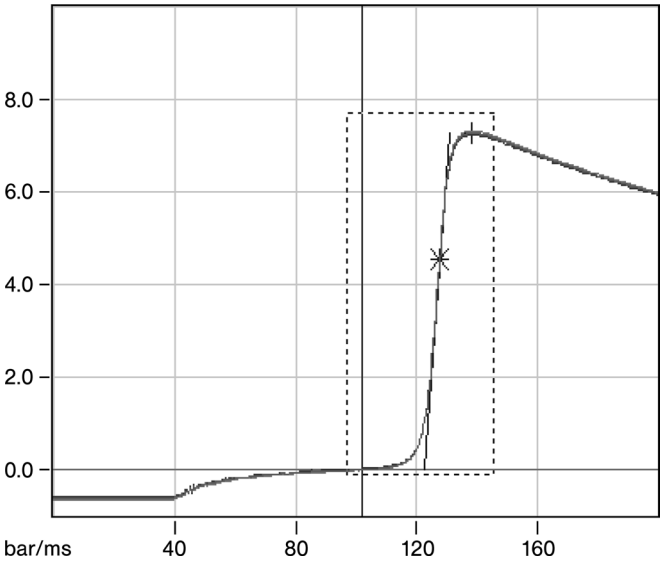

Figure 3.8 Pressure–time record for an explosion.

concentrations (typically from 125 to 1500 g/m^3) the maximum values can be obtained. The difference between the pressure at ignition time (normal pressure) and the pressure at the culmination point is the maximum explosion overpressure.

3.2.2.2 Maximum Rate of Pressure Rise (dp/dt)

It is defined as the maximum slope of the tangent to the pressure vs. time curve.

3.2.2.3 K_{max} Specific Constant

The K_{max} value is obtained by multiplying the maximum rate of pressure rise by the cube root of the vessel volume where the explosion takes place.

3.2.3 Thermal Susceptibility

The following parameters provide very useful information for the characterization of exothermic oxidation processes (Figure 3.9).

Figure 3.9 Characteristic parameters for explosion severity.

3.2.3.1 Maciejasz Index (MI)

This index is obtained as a result of a test for the reactivity to oxygen, particularly to peroxides. This test is suitable to verify the trend or susceptibility to self-ignition of organic substances. The test consists of attacking the sample with hydrogen peroxide, H_2O_2, and then observing its behavior. If the substance has avidity for oxygen, they will combine with each other through an exothermic reaction that will raise the temperature.

The Maciejasz index, MI, is an inverse function of the time, *t*, in minutes, necessary to raise the temperature of the sample by 65 K from the initial temperature (temperature of the environment), when it reacts with the oxygen peroxide.

$$\mathrm{MI} = \frac{100}{t}$$

Self-ignition risk is considered when $\mathrm{MI} > 10$.

3.2.3.2 Temperature of Emission of Flammable Volatiles (TEV)

This test, also known as exothermic reaction decomposition, is of great usefulness to analyze a possible thermal degradation of organic matters generating volatile flammable substances. The testing method consists of heating a portion of the sample to increasing temperatures and then approaching a glowing wire as an ignition source. If the sample produces vapors, these would be more sensitive to ignition than the solid product itself and they can be ignited at lower temperatures (Figure 3.10).

3.2.3.3 Thermogravimetry (TG) Test

Frequently, differential thermal analysis, DTA, is used to measure the amount of heat absorbed and evolved when a sample of product is heated. It is possible to separate thermal analysis into two different techniques: *thermogravimetry* and *differential scanning calorimetry*. In thermogravimetric (TG) analysis the weight of the samples is measured as a function of their temperatures. TG is a very sensitive technique as changes in weight on the order of micrograms can be registered.

The most significant parameters are

- combustion induction temperature (IT),
- maximum weight loss temperature (MLT),
- increase in weight at the beginning of the heating process (IW).

Figure 3.11 shows a TG test with the characteristic points marked on it. The weight of the sample is plotted on the Y-axis, the temperature on the X-axis.

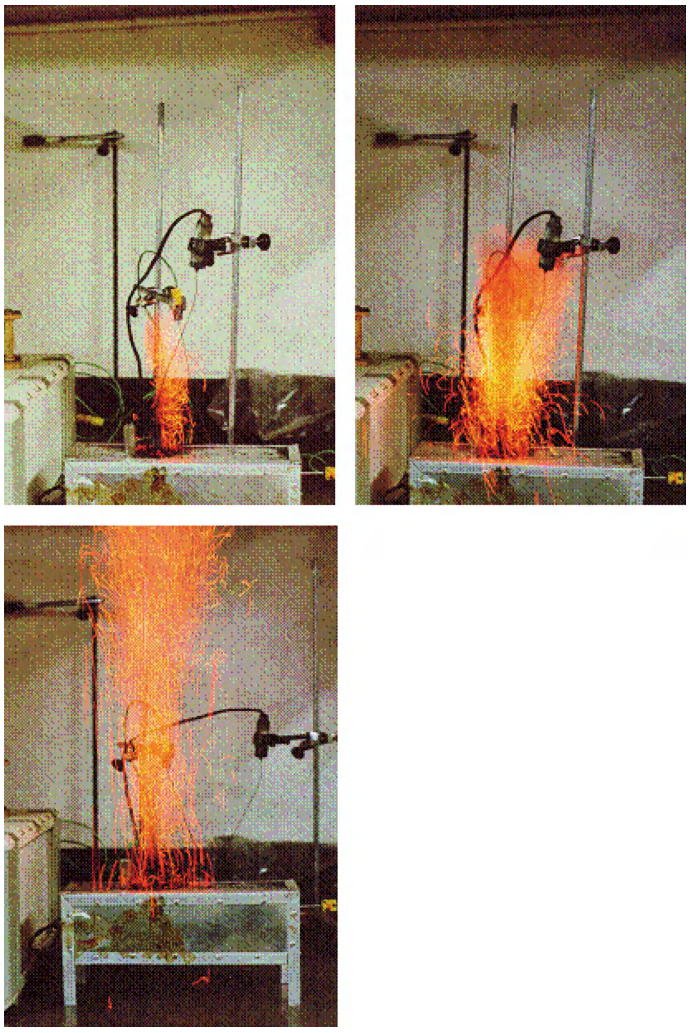

Figure 3.10 Test for exothermic decomposition reaction.

3.2.3.4 **Differential Scanning Calorimetry (DSC)**

The sample is placed in a crucible and heated at a regular rate, previously established. The difference in temperature between that of the sample and that of a reference is measured and recorded against the temperature of the oven so that the exchanges of heat in the sample may be determined.

The parameters used to characterize different substances are

- minimum temperature at which the exothermic reaction begins (initial temperature, IET),
- maximum temperature reached during the exothermic reaction (final temperature, FET),

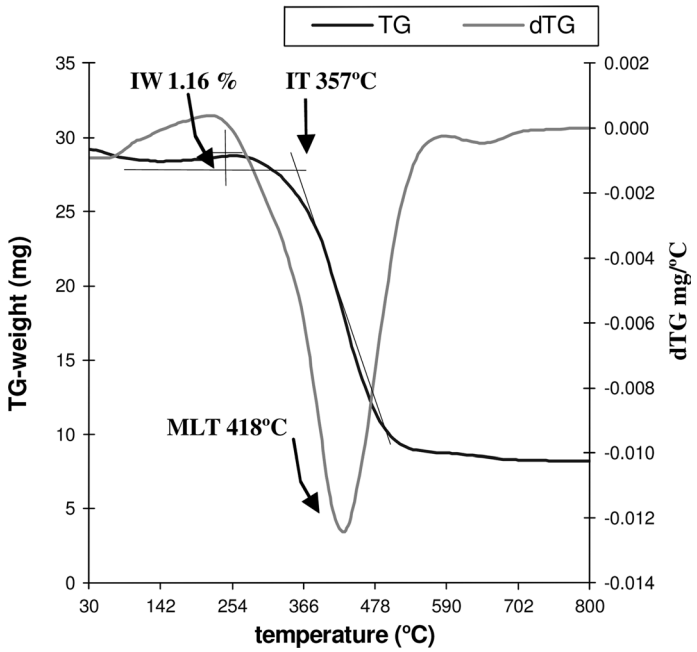

Figure 3.11 Thermogravimetry results.

- temperature at which the fast exothermic reaction commences (change of slope temperature, CST).

Figure 3.12 shows the result of a DSC analysis. The heat flow is plotted on the Y-axis, the temperature on the X-axis.

3.2.3.5 Susceptibility Evaluation: Activation Energy (E_a)

The Cummings kinetic model based on the loss of weight produced during heating coal samples gives us a relationship between the activation energy E_a and the rate of weight loss

$$\ln\left(-\frac{1}{w}\cdot\frac{dw}{dt}\right) = \ln A - \frac{E_a}{RT}$$

where w is the weight of unburned combustible, dw/dt the instantaneous rate of weight loss, A the frequency factor, E_a the activation energy, R the universal gas constant and T the absolute temperature.

Thermogravimetry is used as the fundamental technique. Dust samples are subjected to a heating ramp, increasing the temperature at a constant rate, measuring the loss of weight. After recording the rate of weight loss, a rather simple algorithm can be used to fit a line to the experimental points in the region of the maximum rate, obtaining a sort of apparent activation energy, quite useful for comparing the behavior of substances.

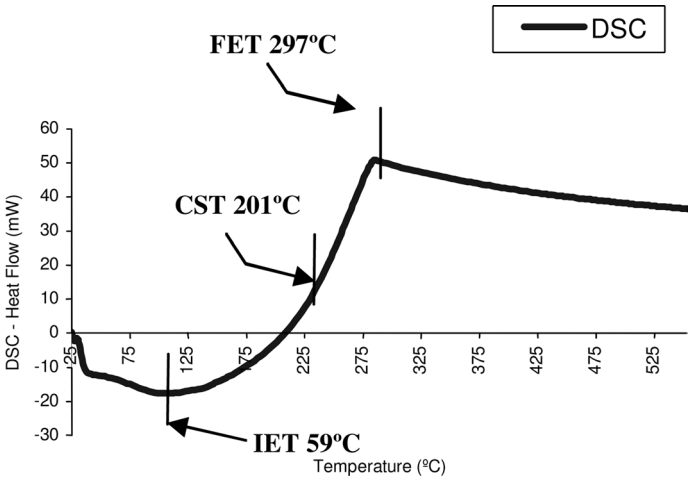

Figure 3.12 DSC results.

During heating of samples, the loss of weight produced can be measured. The activation energy E_a and the rate of weight loss are related through the Cummings kinetic model.

Measuring the decrements of weight (dw) per time unit, plots for dw/dt vs. temperature can be obtained (see Figure 3.13) and, selecting the part of the curve near to the maximum slope and filtering it, a straight line can be fitted, whose slope gives us the activation energy.

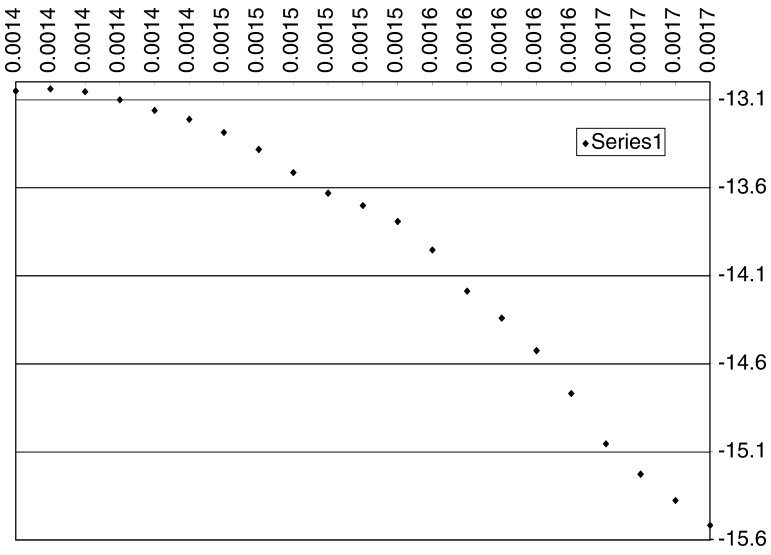

Figure 3.13 Loss of weight vs. temperature plot.

Table 3.1 Self-ignition risk (coal) as a function of activation energy.

Self-ignition risk (coal)	Apparent activation energy (kJ/mol)
Very high	≤79
High	80–89
Medium	90–94
Low	≥95

The E_a value has been particularly used for coals from diverse ranks and origins, showing different self-combustion risks as a function of the E_a values, as presented in Table 3.1.

3.2.3.6 Susceptibility Evaluation: Characteristic Oxidation Temperature (T_{charac})

Standard thermogravimetric analysis in airflow produces a characteristic curve for the loss of weight of the sample when heated at a pre-determined rate. The reaction lasts a long time, so it is not easy to assign a definite temperature for that oxidation. When air is replaced by oxygen, the reaction is much faster, so that a unique value of temperature can be obtained. This value has been already used for comparative purposes among different coals to establish a graduation of the reactivity to the oxygen reaction.

Figure 3.14 shows a TG plot with air and with O_2 showing the great differences of the results obtained.

From this characteristic value of oxidation temperature, substances can be classified in a simple manner, as shown in Table 3.2 for coals.

3.2.4 Thermal Stability

At ambient temperature there are many substances capable of absorbing oxygen from air and interacting with it, producing an exothermic oxidation reaction. When

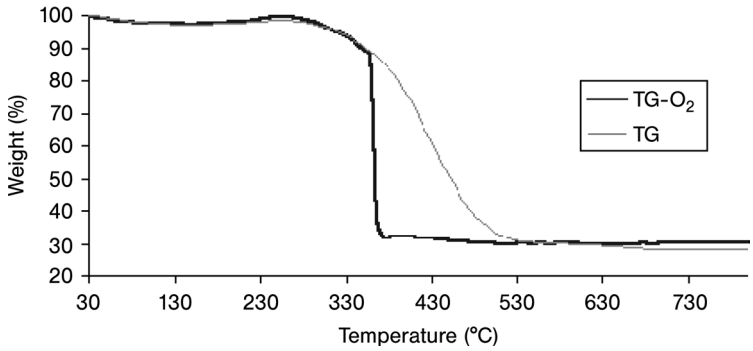

Figure 3.14 Comparison of TG analysis with O_2 and air.

Table 3.2 Self-ignition risk (coal) as a function of characteristic temperature.

Self-ignition risk (coal)	Characteristic temperature (°C)
Very high	≤250
High	250–299
Medium	300–349
Low	≥350

the generated heat is not adequately dissipated to the surroundings, the temperature of the substance rises, leading to the phenomenon known as self-heating.

Self-heating produces a temperature rise which accelerates the material oxidation. At the same time, the temperature increase can produce a decomposition reaction in the material (flammable volatile compounds) and even generate its ignition. This process is known as self-ignition and it is produced in the absence of an external source of ignition.

The experimental procedure is based on a test carried out under isothermal conditions in an oven [9], so that a characteristic self-ignition temperature can be obtained for a pre-determined sample volume (Figure 3.15).

3.2.4.1 Self-Ignition Temperature (SIT)

The classical theory proposed by Semenov based on the assumption of a uniform distribution of temperature throughout the reactants was later formulated by Frank–Kamenetskii considering relatively low thermal conductivity in a vessel with highly conducting walls.

The experimental basis for describing the self-ignition behavior of a given dust is the determination of the self-ignition temperatures (SIT) of differently sized bulk volumes of the dust by isothermal hot storage experiments (storage at constant ambient temperatures) in commercially available drying ovens. The results reflect the dependence of self-ignition temperatures upon dust volume.

A sample is held in the oven at a fixed temperature and the evolution in the sample temperature is observed through the time. Three different behaviors can be observed (Figure 3.16).

- Curve A: subcritical. At the experimental temperature T_A, the sample gains temperature approaching oven temperature. The sample does not produce heat by itself, so that no ignition is observed.

Figure 3.15 Characteristic parameter for thermal stability.

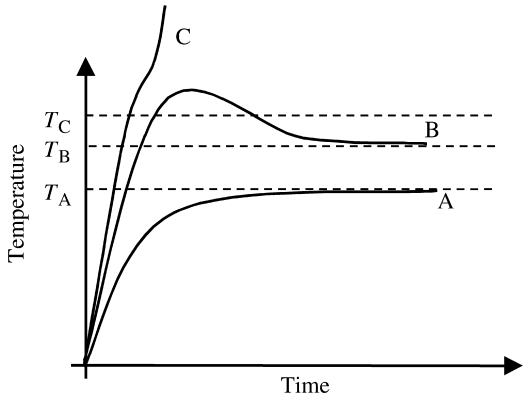

Figure 3.16 Subcritical and supercritical behaviors.

- Curve B: critical. Oven temperature T_B is slightly surpassed during a time, but sample temperature trends again to oven temperature.
- Curve C: supercritical. Heat production surpasses heat loss and non-stationary conditions are reached so that sample temperature increases rapidly over oven temperature, T_C, and ignition is produced.

The temperature of the oven is increased in 5 K until the combustion of the sample is reached. The temperature of self-ignition is the mean between the last subcritical and the first supercritical temperatures. The test is repeated for different volumes of the sample, typically ranging from 15 to 1500 cm^3.

$$\mathrm{SIT} = \frac{(T_B + T_C)}{2}$$

Once the SIT is obtained for different sizes of the test cell, it is possible to relate the temperature and the volume of the sample in an Arrhenius-type diagram. Regression curves containing the results for all the tests show the transition from stationary to non-stationary behavior.

For each test, the interval of time between the positioning of the dust sample in a pre-heated drying oven and the initiation of an ignition, known as the induction time, can also be recorded. Plotting the logarithms of the volume/surface ratios (log V/A) of differently sized dust heaps vs. the reciprocal values of the respective self-ignition temperatures ($1/T$ in K^{-1}) straight lines can be produced, allowing interpolation and extrapolation, to characterize the self-ignition behavior of dust heaps of practical scale (Figure 3.17). Then, not only dimensions of storage leading to ignition can be calculated, but also the required time to reach ignition conditions.

3.2.5
Classification of Solid Dangerous Goods

There are some specific characteristics of solids related to the regulations for labeling, transport and storage of dangerous goods (Figure 3.18):

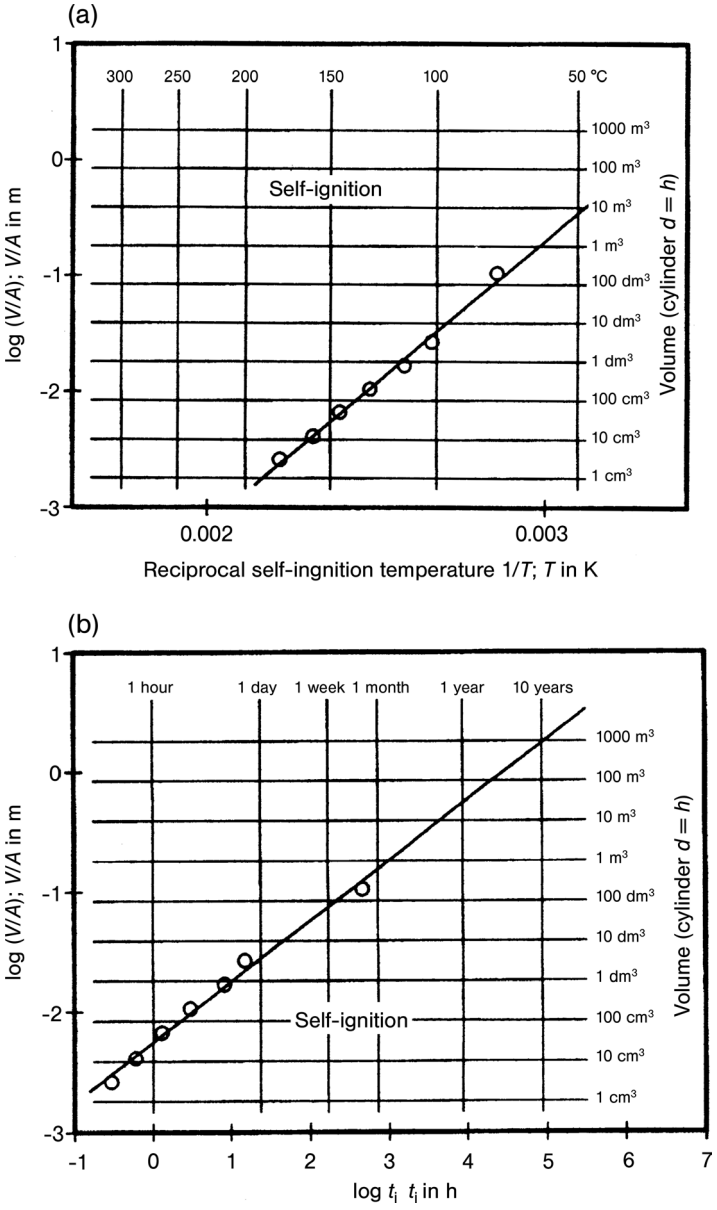

Figure 3.17 (a) Extrapolation of temperature as a function of heap dimension. (b) Extrapolation of time as a function of heap dimension.

Figure 3.18 Characteristic parameters for dangerous goods.

3.2.5.1 Solids which are Readily Combustible

Division 4.1 includes solids which are readily combustible or may cause or contribute to fire through friction and also self-reactive substances which are liable to undergo a strongly exothermic reaction.

In a preliminary test, a flame is applied to the sample spread over a solid ceramic plate in the form of a line deposit (Figure 3.19). Then, if the substance propagates the flame, combustion speed is measured over 200 mm of sample linear deposit.

3.2.5.2 Substances Liable to Spontaneous Combustion

Any substance which is liable to heating up or igniting in contact with air is classified as Division 4.2. The testing procedure consists of introducing a wire basket filled with the sample into an oven pre-heated to 140 °C and observing whether heating or ignition is produced within 24 h or not.

3.2.5.3 Substances which, in Contact with Water, Release Flammable Gases

Division 4.3 comprises those substances liable to become spontaneously flammable or to give off flammable gases when interacting with water (decomposing water into hydrogen and oxygen). The testing procedure consists basically in bringing the sample into contact with water and observing any production of gas.

3.2.5.4 Oxidizing Substances

Division 5.1 includes substances which may, by yielding oxygen, cause or contribute to the combustion of other material, for example ammonium nitrate fertilizer.

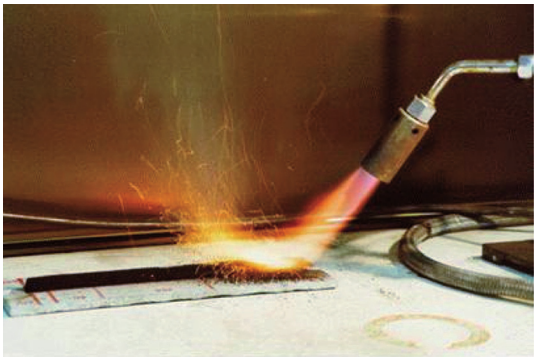

Figure 3.19 Test for readily combustible solid.

The test procedure is based on the comparison of burning behavior of the sample mixed with cellulose as compared to a reference sample. This procedure is applied in order to determine the suitability of a solid material for increasing the rate or intensity of combustion of a combustible material with which it has been homogeneously mixed.

3.2.6 Other Tests

In some countries some traditional methods have been used for a long time. Among them the following can be mentioned (Figure 3.20).

3.2.6.1 Flammability

The ignitability of a dust deposit or layer relates to the ease with which the dust can be ignited by one or more ignition sources, such as an open flame, a smoldering cigarette or a match flame [10].

3.2.6.2 Burning Behavior

A glowing platinum wire is inserted in a small linear pile or dust deposit. If ignition occurs, the severity of the subsequent burning is observed and rated by a class number, from 1 (no burning) to 6 (very rapid burning).

3.2.6.3 Grewer Oven

The test sample and a reference substance are placed into two wire baskets with a volume of 8 ml in an electrically heated furnace at a constant heating rate between 1 and 2 K/min. This test is designed to determine the relative auto-ignition temperature of a product in a hot air stream. It is applied to products which are subjected to elevated temperatures in an air stream for a short period of time [11].

3.2.6.4 Impact Sensitivity

The primary parts of the test apparatus are an anvil upon which the sample is placed, a moving hammer of known contact area that rests on the top of the sample and a falling drop weight that strikes the moving hammer [12].

The sample is tested by placing it between the anvil and the moving hammer. Impact energy is applied to the hammer by a constant-mass weight dropped from a variable height. The amount of energy imparted to the sample is controlled by the drop height. Initiation is observed as production of smoke, fire or an audible pop.

Figure 3.20 Other tests and characteristic parameters.

3.2.6.5 **Friction Sensitivity**

A sample is placed on a mobile anvil of the test apparatus and a stationary wheel is lowered onto the sample such that the sample is pinched between the wheel and the anvil. The wheel is then loaded to a pre-determined load. A swinging pendulum is positioned and released striking the anvil. Initiation is determined by production of smoke, fire or an audible pop [13].

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4
Explosion Risk and Protection

Kazimierz Lebecki

4.1
Essential Conditions for Explosion Occurrence

Fire implies, simultaneously, the presence of: a combustible, an oxidizer and an ignition source which represent together the fire triangle. The phenomenon of explosion with combustible gases, vapors or dusts is more complicated and two other factors are involved. Those are the turbulent mixing of a combustible with air in the explosion range and confinement of the combustible–air mixture completing the fire triangle into the explosion pentagon. The mixing of the combustible with air is particularly important in the case of dust–air mixtures. In the agro, feed and food industries, dust explosions are the cause of serious accidents. Some physical and chemical properties of agro, feed and food dusts, their explosion characteristics and main parameters of explosion propagation will be described.

4.2
Parameters of Dust Explosion; Definitions

Dust: any finely divided solid matter passing a standard sieve (different in various countries). Generally, the limit opening is between 1.0 and 0.8 mm. Laboratory tests proved that particles coarser than 0.425 mm did not contribute to the pressure produced in an explosion vessel. Generally, the particles of size 0.075 mm are considered to fully participate in combustion processes. For dust samples taken in industrial sites the number characterizing sample grain size distribution is the weight percentage of grains passing through different sieves. In many instances, the percentage of the mass of dust passing through a 0.075 mm sieve is designated by d (per cent) $< 75\,\mu m$.

Explosion: rapid combustion of a mixture of gas or dust with air in a confined or partially confined space where heat is generated at a much higher rate than it is dissipated. In the agro, feed and food industries, dust explosions are possible because

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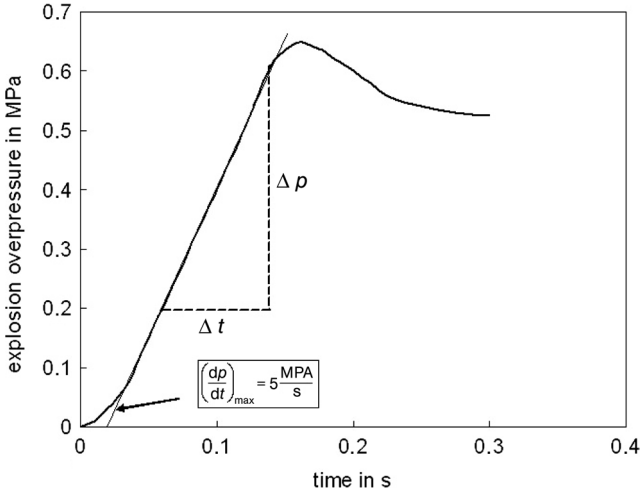

Figure 4.1 Pressure evolution with time during a dust explosion in a closed vessel.

of large amounts of dust formed during transportation and storage of materials. Some explosions may occur from gases evolved from pyrolysis processes or from combustible gases and liquids used in the processes.

According to the EN 1127-1 standard an explosion is "an abrupt oxidation or decomposition reaction producing an increase in temperature, pressure or both simultaneously".

Maximum Explosion Pressure (P_{max}): maximum pressure occurring in a closed vessel during the explosion of an explosive atmosphere determined under specified test conditions. The highest value obtained for a given concentration is seen in Figure 4.1.

Measurements can be performed according to EN 14034-1:2004.

In a partially enclosed volume, the explosion pressure will be lower than the maximum explosion pressure.

Maximum Rate of Explosion Pressure Rise ($dp/dt)_{max}$): maximum value of the pressure rise per unit time during explosions of all explosive atmospheres in the explosion range of a combustible substance in a closed vessel under specified test conditions (no EN standard ready). It is a characteristic of the severity of an explosion and is to be considered for the determination of explosion protection measures (see Figure 4.1). Measured in a 1 m^3 vessel, this value is called the K_{st} value.

Lower Explosion Limit: the minimum fuel concentration which is capable of supporting flame propagation in a uniform dust cloud. For gases there exist lower and upper explosion limits being characteristic parameters for a given gas. In the case of dusts, only the lower explosion limit is measurable. The upper explosion limit is very difficult to determine (generally larger than some kg/m^3). For the majority of agro, feed and food dusts the lower explosion limit or minimum explosive

concentration is about 50 g/m^3. Such a large concentration usually does not exist permanently in industrial workshops. People could not work in such a large dust concentration. Inside the equipment (e.g., grinders) such a concentration is frequently exceeded. However, in many instances, the explosion concentration is only formed by entrainment of layered dust by action of the explosion pressure wave running before the flame front.

Primary Explosion: the initial explosion produced by an ignition of a dust cloud in which the fuel concentration is higher than the lower explosion limit and within the explosion range.

Secondary Explosion: the explosion produced by the propagation of the flame front through the explosive atmosphere produced as a consequence of raising in air dust deposits due to the disturbance caused by the pressure wave of a primary explosion.

Turbulence: random fluctuations in the properties of a fluid (velocity, temperature, density, concentration, etc.) associated with the existence of flow perturbations of varying sizes. Turbulence increases convective heat transfer and mixing, and then the explosion effect.

Venting: this protection measure aims at reducing the pressure produced by an explosion in an enclosure, by providing openings to relieve the volume expansion caused by heating of the gases in the enclosure. The reduced explosion pressure must be as low as possible to avoid the bursting of the enclosure.

Explosion Suppression: this protection measure is aimed at lowering the explosion pressure by rapidly injecting extinguishing agents in a regular shape (length/diameter less than 2) vessel to be protected in order to avoid its bursting.

Note: protection by venting or by explosion suppression is applicable to equipment with limited volumes.

4.3 Some Physical and Chemical Properties of Agricultural Dusts

One of the examples of agricultural dusts is grain dust containing 65.3% of starch, 6.8% of fiber (cellulose), 4.0% of fat, 6.5% of proteins, 9.5% of moisture and 8.0% of ash.

The higher the moisture and ash contents, the lower the explosive properties of dusts. The burning components such as starch, fat, proteins and fibers have a different chemical composition but it is possible to write the general chemical formulae for moist and dry dusts. Possible examples are

- for moist dust, $C_{3.2344}\ H_{6.3800}O_{2.871}N_{0.069}$ + ash;
- for dry dust, $C_{3.574}H_{5.892}O_{2.598}N_{0.076}$ + ash.

The moisture content is defined as the difference of mass of a sample at ambient temperature and after complete drying at 70 °C related to the mass at ambient temperature.

Ash content is defined as the inorganic residue after burning at a standardized temperature. For the organic substances there is another important parameter deciding about explosive properties of the dust. This parameter is called the volatile content and is determined as the loss of mass during the slow heating of the sample in the temperature range up to 900 °C. Volatiles are simply the gases which are released from the grain during the heating.

According to the "oxidizing model" the burning reaction of the dust can be written as

$$(\mathrm{D}) + \mathrm{O_2} = (\mathrm{D})\mathrm{O_2}$$

where (D) symbolizes the dust. For organic dusts such a reaction is less probable and occurs at the high temperatures of about 2000 °C.

According to a "volatile (V) burning" model the reaction can be written as

$$(\mathrm{D}) + \text{heat} = \mathrm{V} + \mathrm{O_2} = \text{burned gases}$$

In Table 4.1 the values of volatile, ash and moisture contents for several grain dusts are given. In the last column of the table, the percentage of mass content of grains with diameter below 75 microns is given, as a characteristic of dust grain size.

The calorific value of the grain dust was in the limit between 15 and 16 MJ/kg. The current specific gravity being 1450 kg/m has grown to 1560 kg/m for a sample containing 20% of ash and to 1700 kg/m for a sample containing 42% of ash.

It is not excluded that incombustible matter determined as ash could be a mechanically added mineral dust.

Table 4.1 Explosibility and physical parameters and K_{st} values of some agricultural dusts (measurements at experimental mine Barbara, Poland).

Number	Dust	K_{st} (bar m/s)	Volatile content (%)	Ash content (%)	Moisture content (%)	$d < 75$ µm (%)
1	Corn (A)	110	87.0	10.6	10.6	99.0
2	Corn (A)	70	82.9	5.9	11.4	46.0
3	Corn (A)	140	88.5	1.6	11.2	78.0
4	Corn (A)	65	86.0	2.3	11.9	65.6
5	Corn (A)	150	87.5	1.5	11.4	87.7
6	Corn (A)	110	85.2	1.7	11.5	68.0
7	Corn (A)	90	86.8	1.9	11.5	71.5
8	Wheat (P)	60	79.5	22.2	8.2	46.0
9	Wheat (P)	70	82.3	20.0	9.1	85.0
10	Wheat (P)	75	81.3	7.4	9.0	76.0
11	Wheat (P)	75	82.8	5.4	8.2	71.8
12	Wheat (P)	100	94.3	6.7	9.2	75.5
13	Wheat (P)	75	78.4	6.6	10.3	55.2
14	Wheat (P)	80	83.9	8.0	10.1	67.0
15	Wheat (P)	80	85.7	42.0	6.8	92.5

A = dusts from USA, P = dusts from Poland.

4.4 Explosion Characteristics

There are two groups of parameters characterizing the explosion risk due to dust–air mixtures in industrial plants:

- flammability parameters – temperature of ignition of dust cloud, minimum temperature of dust layer, and minimum ignition energy,
- explosibility parameters.

Flammability parameters are: minimum ignition temperatures of dust cloud and dust layer and of explosive gas and vapor atmospheres, and minimum ignition energy.

Note: for combustible gases and vapors, the maximum surface temperature of the equipment is to be determined by reference to the ignition temperatures of gases and vapors. The methods of determination of subsequent parameters are internationally standardized.

For a convenient choice of the maximum surface temperature of the equipment to be used in the presence of dust, the ignition temperatures of dust layers (5 mm thickness) and of dusts clouds must be determined.

Using the IEC standard 31 H WG 2, sheet 21 (now EN 50281-2-1:1998), extreme values for the 5 mm layers were respectively 493 K for wheat dust and 840 K for dextrine.

The minimum ignition temperatures for dust clouds could be determined in the Godberg–Greenwald furnace (IEC standard 31 HWG 2, sheet 2.2, now EN 50281-2-1:1998) for typical agricultural dusts (as described in Table 4.1) and are between 614 K for wheat dust and 793 K for cornstarch.

Minimum ignition energies were determined for some agricultural dusts, according to the IEC 31 H WG 2, sheet 2.4 method. The values are in the range 30 millijoules for cornstarch to 107 millijoules for wheat flour with a 10% moisture content.

Explosibility parameters are: lower explosion limit (for gaseous mixtures upper explosion limit also), maximum explosion pressure, maximum rate of pressure rise and the constant K_{st}.

Minimum explosion concentration is determined according to IEC: 31 HWG 2, sheet 2-5. The apparatus used is a spherical 20 L chamber. Minimum explosion concentration C_{min} is determined from the curve "pressure–concentration". The minimum explosion concentrations are in the range 30 g/m^3 for cornstarch and 750 g/m^3 for barley and oat dusts. The minimum explosion concentration for dusts and gases are on the same order of magnitude if expressed in gravimetric units (g/m^3).

Maximum explosion pressure is determined in a spherical chamber with the volume of 20 L, by recording the curve "pressure–time" (Figure 4.1). From the curve the values of maximum explosion pressure and maximum rate of pressure rise are calculated. In Figure 4.2 the characteristics of explosibility determined at experimental mine Barbara (Poland) are given. For wheat dust, the maximum pressure is 8.4 bar and the maximum pressure rise is 313 bar/s. The maximum explosion

pressure of agricultural dusts are in the range 4 bar for rye dust to 10 bar for cornstarch. The maximum rate of pressure rise is in the range 27 bar/s for rye dust to 200 bar/s for cornstarch. The maximum rate of pressure rise is considered to be the best characteristic of explosion severity of dusts and gases because of the so-called

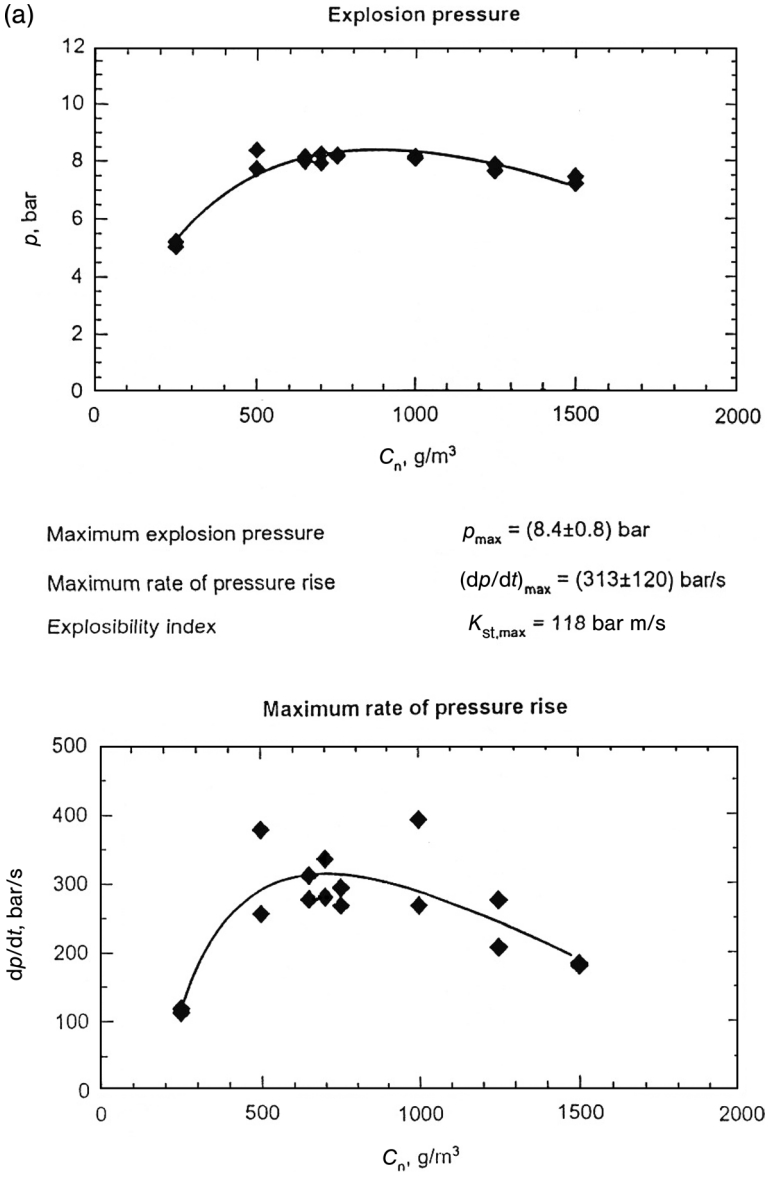

Figure 4.2 (a) Characteristics of explosibility of wheat dust from Polish grain elevator. (b) Explosibility range of grain dust as measured in the experimental mine Barbara (Poland).

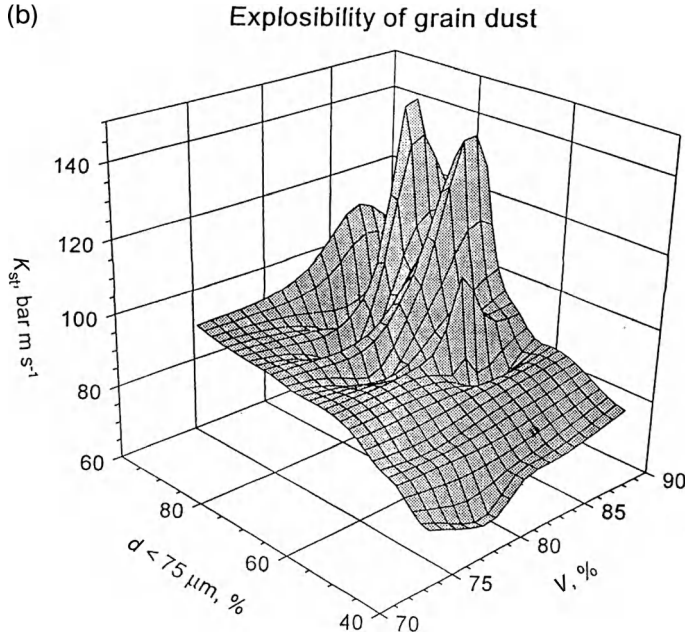

Figure 4.2 (*Continued*).

"cubic law." The mathematical formulation of the cubic law is

$$(\mathrm{d}P/\mathrm{d}t)_{\max} V^{1/3} = K_{\mathrm{st}} = \text{const.}$$

The K_{st} value is considered as a measure of dust explosibility and permits us to calculate the explosion effects in a given volume. This value is the basis of classification of dust explosibility to the classes St1, St2 and St3.

Note: $P_{\max}$ values determined in the 1 m^3 vessel (EN 26184/1) and the 20 L sphere according to special procedures are identical. $(\mathrm{d}P/\mathrm{d}t)_{\max}$ values are volume dependent using the cubic law. Operational procedures in both sets of apparatus were defined assuming the application of the cubic law.

The data from Table 4.1 were used for graphical presentation of dependences of K_{st} on subsequent parameters. Moisture and ash contents were summarized as one common parameter – incombustible matter content. Figure 4.3 represents the relation $K_{\mathrm{st}} = f\{(W + A), V\}$, Figure 4.4 represents the relation $K_{\mathrm{st}} = f\{(W + A), d < 75\ \mathrm{mm}\}$. The general symbols W, A and V mean respectively moisture, ash and volatile contents.

The regularity of the functions seen in Figures 4.1, 4.3 and 4.4 enables us to find the general influence of dust physical properties on its explosibility. From the figures it is seen that the functions are not affected by the origin of the dust (wheat, corn, soy). Some do not fit the curves but it probably results from non-adequacy of some characteristic parameters of dusts. One may assume that grain size would be better characterized by specific (internal) surface area according to section 1.2.1 rather than content of grain with diameter below 75 μm. Also, the incombustible content

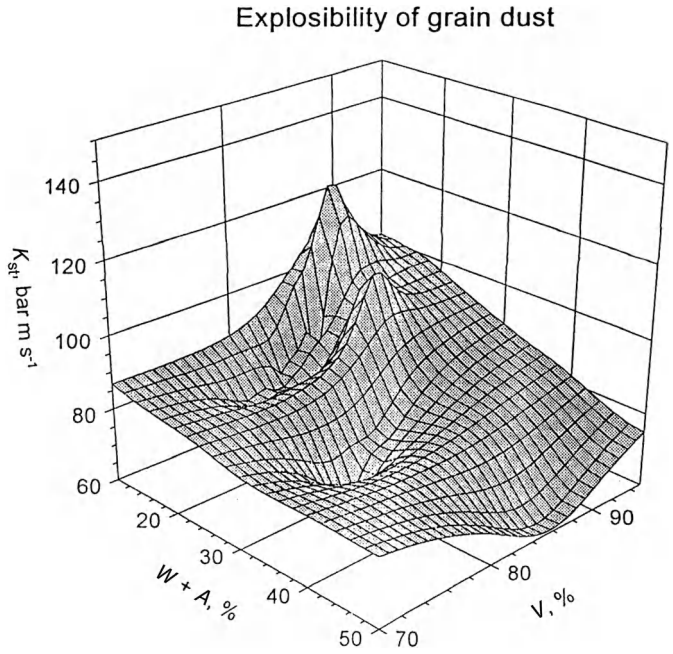

Figure 4.3 K_{st} as a function of incombustible matter and volatile matter content.

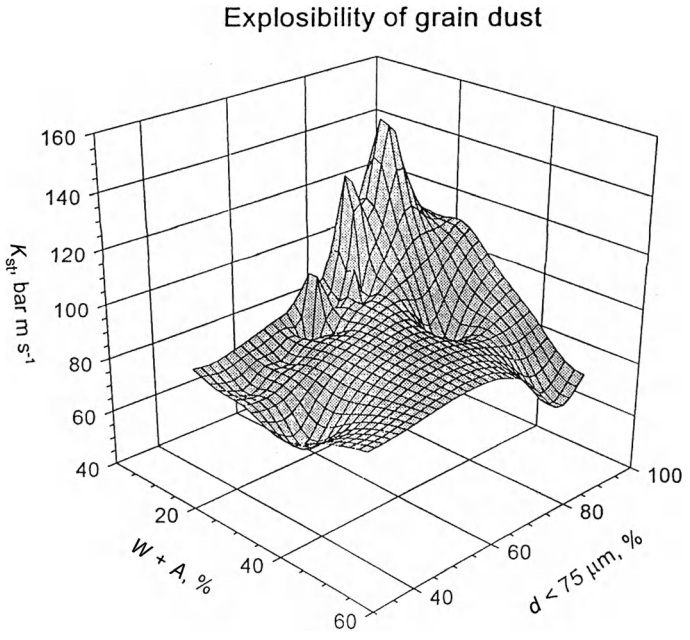

Figure 4.4 K_{st} as a function of incombustible matter content and a particle fraction $d < 75\,\mu m$.

should be determined by incineration preferably at the temperature of 480 °C rather than 850 °C. But, accepted parameters are easily determined with commonly accepted methods.

The simplest analytical formula describing the dust explosibility is

$$K_{st} = c_1 \exp[c_2 V + c_3(W + A) + c_4(d < 75\mu m)]$$

From the values of K_{st} given in Table 4.1, by the least-squares method, one can calculate the c coefficients. The numerical values are given below:

$$K_{st} = 13.64 \exp[0.0166V - 0.0244(W + A) + 0.024(d < 75\mu m)] \quad (4.1)$$

The maximum deviation of the calculated and measured values is 25.8 bar m s^{-1}. Equation (4.1) may serve as a general consideration on the explosibility of grain dusts. According to the general rules, dusts with $K_{st} < 200$ bar m s^{-1} belong to the class St1 of lowest hazard. The dusts with K_{st} in the range 201–300 bar m s^{-1} are more dangerous (class St2) and the dusts with $K_{st} > 300$ bar m s^{-1} are the most dangerous (class St3).

Putting into Equation (4.1) real values of the moisture, ash and volatile contents one sees that in the majority of cases the grain dusts belong to the class St1. In some cases, for example fine dry maize dust, the class St2 is possible. In such an extreme case, the detonation in long galleries is not excluded. Agricultural dusts generally belong to the class St1; in some particular cases the class St2 appears.

4.5 Propagation of Explosion

All parameters mentioned above describe the processes of combustion in closed vessels of relatively small volume where combustion is relatively slow and runs without considerable gas flow. In long galleries, existing for example in grain storage silos, the course of explosion could be very violent and different parameters are needed to characterize the explosion. Figure 4.5 represents the scheme of explosion of gas or dust in a long gallery. Generally, the ignition begins at the closed end of the gallery, although it is not obligatory. A short time after ignition the flame front is formed filling the whole cross section of the gallery. The flame front moves like a piston compressing the gases ahead, causing the flow of gases, particularly air. This flow is turbulent and the turbulences cause an increase of the reaction rate. That is a reason for flame acceleration. The lower part of Figure 4.5 represents the idealized image of events suitable for mathematical modeling. The gas blows dust deposits introducing them into the zone of the flame and combustion of grain dust begins. The process continues and is called flame propagation. It lasts as long as the fuel (deposited dust) and oxygen (from air) exist. In Fig. 4.5 Co_t represents the propagation length of the compression wave at time t and W_t the propagation length of the flame at time t, respectively.

Dust explosion initiated in a pre-determined place of a pipe or duct may develop and propagate if sufficient amounts of dust and their favorable distribution exist.

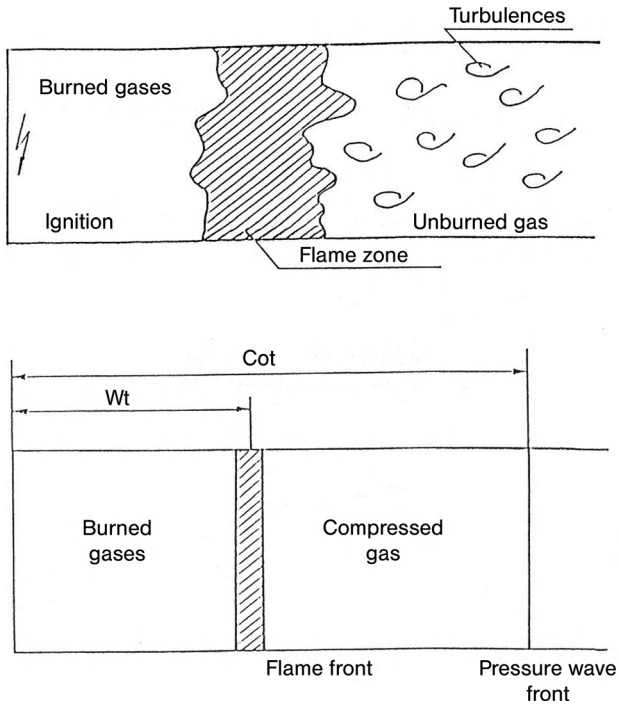

Figure 4.5 Scheme of explosion course in long gallery.

In grain industry plants; there are long ducts and pipes with a considerable amount of deposited dust on the walls where an ignition source may occur.

There are two basic characteristics of the propagated explosion: the lowest dust concentration enabling explosion propagation and dynamics of explosion characterized by the flame front velocity and static pressure. Both problems will be described below. The lowest concentration enabling explosion propagation has been determined in a surface gallery 100 m long with the cross section of 2.9 m^2 (diameter 2.0 m). In such dimensions the dispersion of dust is almost homogeneous. The gallery is equipped with a sensor system to measure and record the explosion parameters: flame front position vs. time, pressure wave amplitude, local dust concentration and temperature of glowing particles. A few series of experiments were done in the gallery to investigate the lowest limit conditions of flame propagation in the dusty zone.

The information received from those experiments is very important to estimate the hazard in industrial plants. The best method of fighting fire and explosion is to follow the rule "no fuel – no fire and explosion." The easiest conditions of explosion propagation are in the case of primary explosion taking place at the closed end of the gallery, duct or pipe. The fuel amount needed for explosion propagation is less in this case. The experiments were performed in such a way that the primary explosion (ignition source) took place at the closed end of the gallery and the dust was distributed closely to the ignition source. There are many ways to distribute dust

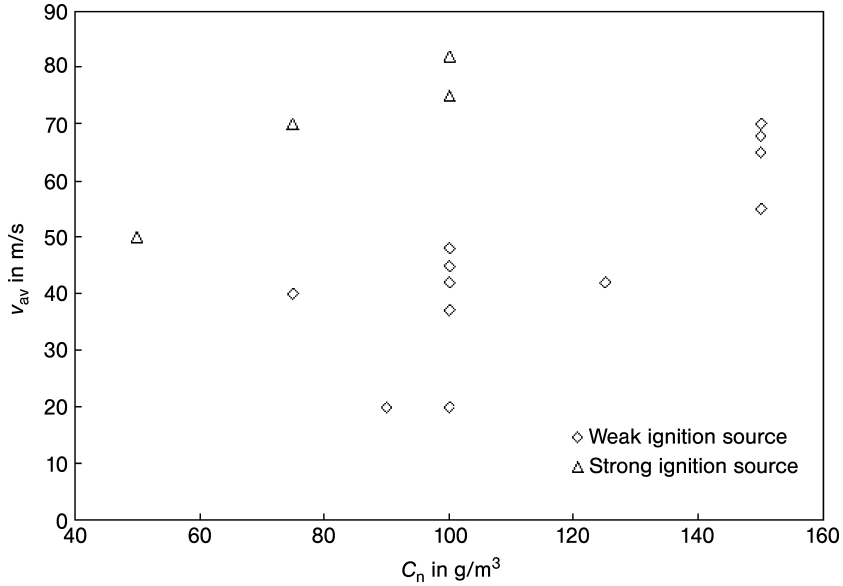

Figure 4.6 Relation between average flame velocity and nominal grain dust concentration in the 100 m long, 2 m diameter surface gallery.

along the gallery and its cross section. The combustion supporting flame propagation takes place in the dispersed dust–air mixture created by the action of a pressure wave blast resulting from the combustion of 10 m^3 of a methane–air mixture at stoichiometric concentration. In these conditions, the dust–air mixture is homogenous or not, depending on its combustion effectiveness. The factor controlling this relation is the dust distribution in the duct. The main part of the results obtained from the investigation is presented in Figure 4.6.

The ability of a flame to propagate continuously from ignition source along the 60 m long dusty zone in the gallery was investigated. The layered dust was distributed on the floor in one or several continuous parallel path(s) with continuous density along the whole length. The dust amount per unit of zone length divided by the gallery cross section gives the nominal dust concentration C_n marked as an abscissa in Figure 4.6. The ordinate is the average flame velocity v_{av} over the distance of the undisturbed flame run. The disturbance comes from the rarefaction wave which moves towards the closed end of the gallery. The rarefaction wave is formed at the moment of leaving the gallery by the pressure wave.

The results obtained with the ignition source alone are marked in Figure 4.6 by diamonds. In some experiments a stronger ignition source was used. It consisted of 15 kg of grain dust placed closely to the methane chamber at the distance of 10 m (the dusty zone with nominal concentration of 0.5 kg/m^3). The results of these experiments are marked by triangles.

It is seen from Figure 4.6 that the undisturbed flame speed depends on the dust concentration C_n. The disturbing factors are the primary explosion and the reflected

pressure wave. But, the flame velocity depends also on the ignition source. With the same dust concentration the flame velocity may be different depending on some differences in dust distribution and other hazardous conditions such as initial pressure rise in the primary explosion. But, generally, with the weak methane ignition source the nominal dust concentration enabling the explosion propagation in a long duct or duct is $C_n = 0.075\ kg/m^3$.

With the stronger methane–dust ignition source this concentration is lower: $C_n = 0.050\ kg/m^3$. The methane–dust ignition source may be considered as the strongest under typical industrial conditions (its flame range is over 40 m). As a conclusion we can state that the lowest safe concentration of the dust initially covering the walls of pipes and ducts is about $0.050\ kg/m^3$ ($50\ g/m^3$). However, in some favorable conditions, the uninterrupted flame propagation is possible with a slightly lower concentration. From the plot of the function $V_{av}(C_n)$ it is seen that there exists a critical value of flame velocity for uninterrupted propagation along dusty zones. The value of the critical velocity depends on duct geometry and dust distribution. To prove the influence of changes of the dust concentration along the duct, some experiments illustrating this effect were performed. In the test number ST 3335 (Figure 4.7) the dust layer 0.20 m long with a concentration of $0.1\ kg/m^3$ was formed closely to the methane chamber. Next, 10 m of the duct were clean and then another 20 m layer was formed. The nominal dust concentration of $0.1\ kg/m^3$ is only 30% higher than the limit concentration of flame propagation in uninterrupted layers. From Figure 4.7, it is seen that the flame jumped over the dustless zone and then the propagation was stable along the secondary zone. The final flame velocity was almost the same as at the beginning of the secondary zone. The effect then repeats. Another arrangement in the test ST 3334 was the length of the clean zone ~20 m, the same as the first dusty zone. From Figure 4.8, it is seen that in the clean zone the flame slowed down.

This second experiment confirmed the general rule resulting from experiments: the concentration limit of the flame propagation grows due to non-homogeneous dust distribution if the dustless zones are not shorter than the dusty ones.

4.6
Dynamics of Explosions in Long Ducts and Galleries

A growth of the dust concentration above the limiting value causes the adequate growth of explosion dynamics. The scale of growth was tested in an underground gallery, 400 m long with the cross section of $7.5\ m^2$. The gallery was equipped with a sensor system to measure and record the flame front position and pressure wave amplitude vs. time. To obtain the effective explosion development the length of the dusty zone was 200 m. The primary explosion was achieved by the combustion of stoichiometric methane–air mixture in a volume of $25\ m^3$ placed in the chamber formed at the closed end of the gallery. With the gallery cross section of $7.5\ m^2$, the thickness of the methane layer is the same as in the surface gallery. Some explosions of maize dust were performed with nominal dust concentrations of 100, 150 and

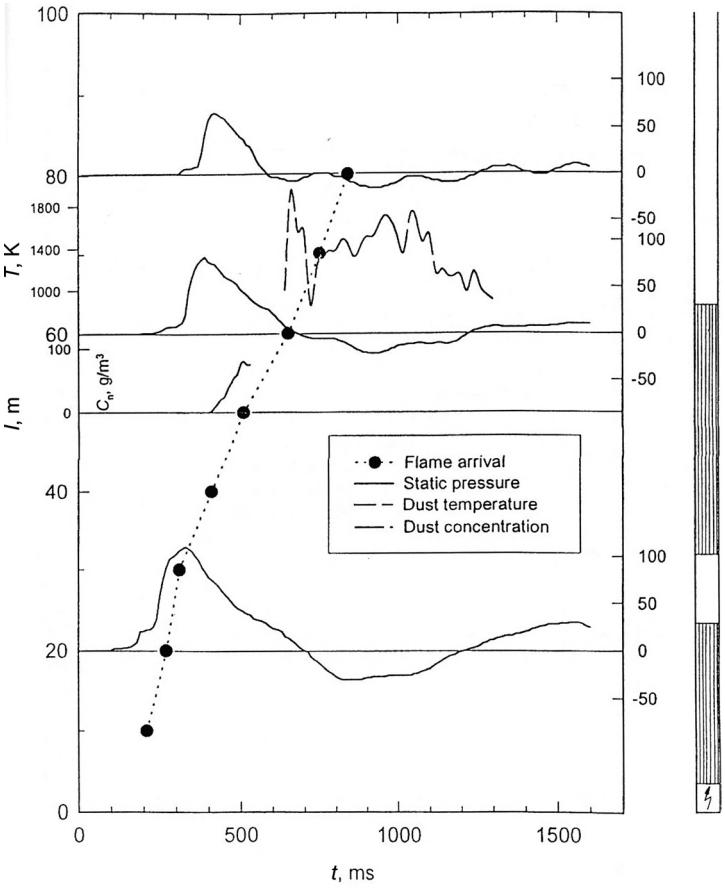

Figure 4.7 Wave diagram of ST 3335 grain dust explosion in the 100 m long surface gallery.

200 g/m^3. The flame velocity and static pressure at pre-determined points of the gallery were measured. Table 4.2 summarizes the results showing the growth of explosion dynamics with nominal dust concentration.

Additionally, Figure 4.6 shows the flame velocities with possible acceleration along the dust path. The information is completed by Figs. 4.7 and 4.8 showing the measured parameters as a function of time for the strongest explosion with a minimal dust concentration of 200 g/m^3. The process of formation of the pressure wave is seen. The test number CH2400 is particularly interesting due to the very strong pressure wave formed at the distance of 200 m from the closed end of the gallery. The observed phenomenon is called transition to detonation. The amplitude of the wave exceeds the measuring range of the pressure sensor (15 bar). Such a high pressure and high flame velocity (more than 2000 m/s) indicate that in favorable conditions the detonation of grain dust is possible, causing a real catastrophe.

As a conclusion of these experiments we can say that with rather large ignition sources

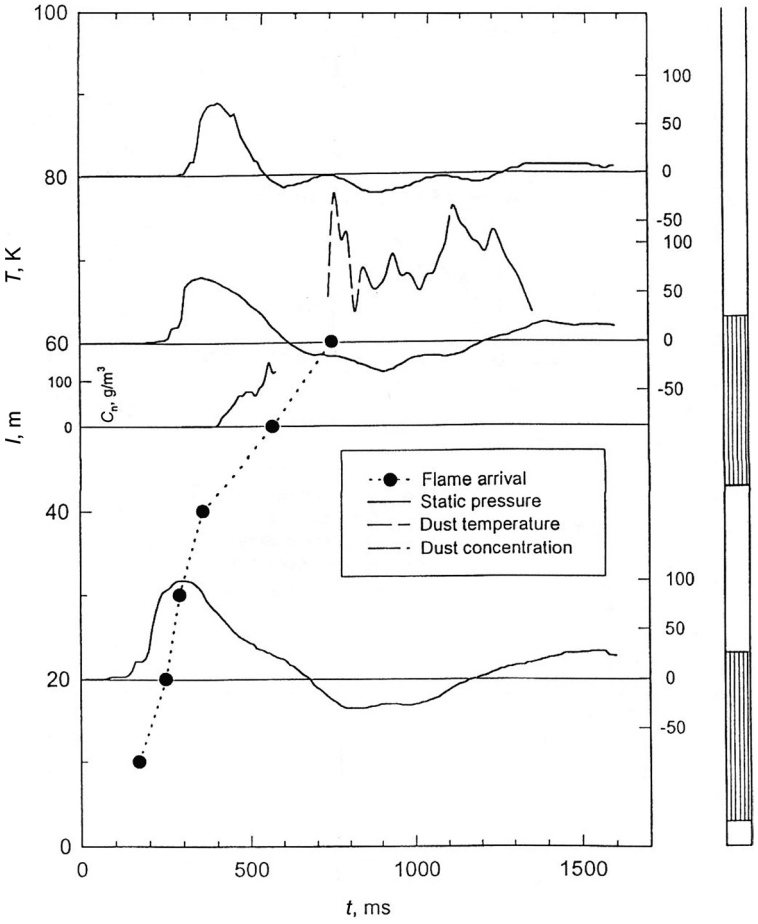

Figure 4.8 Wave diagram of ST 3334 grain dust explosion in the 100 m long surface gallery.

Table 4.2 Maximum static pressure and mean flame velocity in 7.5 m^2 underground gallery at different distances (ΔL) from ignition point; C_n – nominal dust concentration.

	$C_n = 100\ g/m^3$		$C_n = 150\ g/m^3$		$C_n = 200\ g/m^3$		$C_n = 200\ g/m^{3a}$	
ΔL (m)	P_{stat} (bar)	V_f (m/s)	P_{stat} (bar)	V_f (m/s)	P_{stat} (bar)	V_f (m/s)	P_{stat} (bar)	V_f (m/s)
40	0.60	165	1.00	125	2.65	170	5.80	280
80	0.25	110	1.75	135	3.10	220	4.80	255
120	0.50	100	2.20	210	4.00	450	710	670
160	0.50	80	2.50	255	5.40	500	–	830
200	0.50	70	4.00	330	5.60	670	>15.00	2000

[a]In this case the gallery was drier than in the previous experiments.

- explosion can propagate continuously along the layered dust path in galleries and pipes if nominal dust concentration is higher than 50 g/m^3,
- if nominal dust concentration in the long duct is higher than 100 g/m^3 a flame can accelerate up to detonation, when the propagation path is about 200 m.

4.7
Causes of Fires and Fire–Explosion Protection

4.7.1
Age of the Facilities, Maintenance and Repair Work

Explosions and fires occurred equally in old and new plants. In some cases, accidents took place in the commissioning phase of the plant and were the consequence of the absence of a detailed risk assessment and efficient application of preventive and protective measures. The administrative authorization procedure may give the opportunity to control the adequacy of measures taken by reference to the possible accidents.

On many occasions, maintenance and repair work were initiating conditions for the accidents: cutting and welding operations shall not be undertaken without a hot work permit and are in many instances external ignition sources.

4.7.2
Nature of Processed Materials

Many different types of materials are involved in accidents: grain, fodder, oil, seeds, dried milk and sugar. All these materials are combustible but their combustibility, explosibility, flammability and fire and explosion propagation are strongly influenced by physical properties like moisture and ash content, grain size, ageing and so on. These properties are also to be related to the equipment used for processing the materials. Inadequate operating procedures, such as a too high temperature, too great flows, too humid materials and too fine grinding may induce conditions easing ignition, for example.

4.7.3
Ignition Sources

Before storage, the materials are processed in a lot of mechanical equipment, such as conveyors, bucket elevators, mixers, grinders and so on in which friction is quite unavoidable. Many accidents were reported in bucket elevators as a consequence of friction processes. Monitoring of involved equipment may increase the safety level in the facilities if convenient preventive measures are applied.

Drying processes are also mentioned in many accidents owing to the fact that a too high temperature and/or a too long drying time are used. The ignition occurs in the dryer itself or in the subsequent storage in which too hot materials were received.

With maize, lucerne, oil seeds (sunflower, soybean and so on) and milk, smoldering fires occurred in storage; such fires are difficult to fight and imply specific means (inerting of the cells by inert gases and so on).

Self-heating and self-ignition of dust layers on a hot surface are also mentioned as initiators of fires and explosions.

A significant number of fires and explosions are initiated by welding and cutting operations.

Some evidence of accidents by electric or electrostatic spark ignition is related to dusts with very low ignition energies such as sugar.

4.7.4 Plant Operation

Many accidents took place during starting and stopping operations in which large dust clouds or dust layers may be obtained. This is particularly the case in filling and emptying processes in cells. Changes of materials in the same plant are also at the origin of fires and explosions (drying milk with different fat contents; dried grain instead of normal humidity grain).

4.7.5 Type of Buildings and Facilities

On many occasions, the storage cells, the underground or above-ground galleries and the buildings were built in such a way that during explosions flying debris was blown out hundreds of meters apart. Such a situation is related to the absence of considering secondary explosions in these premises. This aspect should be dealt with at the design stage.

4.7.6 Equipment for Dust Collection

Equipment in which dust, in some cases as a by-product, is collected was also involved in explosions, but it is not generally possible to be sure that the explosion was initiated there. A detailed risk assessment should be carried out when it is decided to install such equipment in a plant for hygiene or economic reasons. Collected dust must not be allowed to stay in the equipment or its surroundings and must be evacuated as soon as possible.

4.7.7 Plant Automation

When increasing the automation of a plant, it is an absolute pre-requisite to define safe operating conditions. Special attention should be paid to the monitoring of the physical properties of the material and to the control of the equipment, particularly the temperature control. An early detection of friction or choking in equipment is essential. It is highly recommended to estimate the SIL levels according to EN 61508.

4.7.8
Human Factor

When it was possible to have a discussion with people directly involved in the operation of a plant that had suffered an accident, they were generally not aware of the possible consequences of such fires and explosions and they were astonished by the speed of the phenomenon. It means that training of personnel in this matter is essential and should be updated regularly.

4.8
Fire and Explosion Prevention and Protection in the Storage of Agro, Feed and Food Products

Every industrial plant should be the object of an explosion and fire risk assessment.

It depends on the identification of existing explosion and fire hazards dealing both with the probability of their occurrence and the degree of possible damages, considering especially possible spreading.

The prevention will deal with the probability of explosion and/or fire occurring, which is to be evaluated by the explosion and fire parameters of a combustible system. Further, the properties and efficiency of ignition sources on the combustible (systems) shall be determined.

It must be taken into consideration that the explosion and fire parameters are determined at the laboratory scale under specified test conditions. For risk assessment, it is therefore necessary to consider actual operating conditions under which the combustible substances, and oxidizers, are processed or stored (influence of working pressure and temperature, the state of matter movement (at rest, laminar or turbulent flow), space geometry and others). It is also necessary to assess the risk not only under the normal working conditions but also at starting and shutdown of a plant, at maintenance and repair works and in a case of faults and failures. In these unusual working regimes, the kinds of combustible substances, their amount and space distribution may change. New ignition sources occur (e.g., welding sparks during repair works using welding, hot spots by overloading of a belt, etc.).

4.9
Explosions

4.9.1
Prevention

The prevention of dust explosions consists in eliminating one or more of the conditions included in the "pentagon of explosion." Preventive action can be taken on the following:

- the combustible element: dust,
- the source of ignition,
- the oxidizer: the oxygen of air.

4.9.1.1 **Limitation of Dust Emission**

As far as combustible dust is concerned, and to the greatest possible extent, when working with agro, feed and food products every effort should be made to avoid creating unnecessary dust clouds in which a "primary" explosion can occur; dust emission should also be prevented outside the equipment to avoid dust deposits in premises, as raising of dust can cause a "secondary" explosion.

Within agro, feed and food product silos, major dust emissions occur at transfer points in gravity conveyor systems and also in installations in which products undergo special treatment (cleaning, drying, etc.).

The reduction of dust emission can be achieved by means of constructive measures applied to the installations concerned (e.g., reduced drop heights), preventive measures in respect of the products stored (preliminary cleaning and special treatment) and the introduction of dust control equipment (dust filter unit).

If, despite these measures, there is still a problem of dust, then the installations concerned or the points of dust emission (when practicable) will need to be made sufficiently dust-tight so that the dust cannot escape.

Residual dust emitted within installations to which the above measures have not been applied will settle by sedimentation on the ground and the walls of the building; such accumulations of dust created for example along conveyor lines (due to spills) will form deposits liable to contribute to a dust explosion.

In order to reduce the risk of an explosion, dust deposits should be removed regularly so that in the event that dust is raised its concentration in air remains outside the explosion range.

It is essential to adapt design to the building(s) concerned in order to limit dust deposits especially in areas that require cleaning but which are difficult to get at.

Limiting dust emission and deposits to an appropriate threshold, so as to reduce very appreciably the probability of an explosion, will not be achieved, despite the above measures, unless the personnel involved are made aware of the hazards created by dust and plant procedures and take due notice of this problem (silo design and maintenance, cleaning procedures, etc.).

Whilst these measures will not, generally speaking, eliminate the risk of an explosion, they will basically make it possible to prevent an explosion spreading and turning into a major disaster.

4.9.1.2 **Limitation of Ignition Sources**

Effective ignition sources causing an explosion can have external origins:

- thermal (hot spots, friction),
- electrical (short circuits, etc.),
- mechanical (impact, shock, spark),
- electrostatic (discharge, etc.).

They could also be internal: self-heating and self-ignition of the product.

The source of ignition may have its origin inside or outside the installation.

An ignition source from within the installation may come from a normal phenomenon (such as heat generated by a diesel or electric motor) or from an abnormal occurrence (such as accidental friction).

An ignition source from the outside often comes from other storage equipment (conveyors, dust control unit) and may have very different origins: incandescent particles, foreign bodies, etc.). Another very frequent origin results from repair or maintenance operations (hot spot working).

The flames from an explosion occurring in an adjacent building may also be an outside source of ignition.

Self-heating, self-ignition of stored agro, feed and food products or an explosion due to fermentation gases could also be effective ignition sources.

The prevention of explosions means the elimination of any and all effective ignition sources.

To prevent an explosion, measures must be taken such as to prevent the possibility of any sources of ignition, notably by choosing convenient equipment and materials to be used, by the design of equipment and by using controlling and monitoring systems able to detect malfunction.

The definition of specific measures must take into account the nature of any source of ignition likely to occur together with the ignition characteristics of the dust.

Another method of eliminating effective ignition sources is to use a fire-extinguishing substance for advance inerting once the source has been detected. This means of preventing an explosion is used mainly in installations where the product is conveyed by gravity (conveyor) or by an outside means (pneumatic conveyor).

4.9.1.3 **Reduction of Oxygen Content**

Reducing the oxygen content by the addition of an inert gas can take the dust out of the explosion range.

To avoid any risk of explosion, an inert gas can be introduced into the enclosure within the installation so as to prevent dust in suspension from causing an explosion in the presence of a source of ignition.

Various inert gases may be used for this purpose; N_2, CO_2, combustion gases and so on.

The maximum admissible O_2 content required in order to prevent an explosion depends on the type of product stored and also on the type of inert gas used.

As a rule, the oxygen content should be reduced to a limiting oxygen concentration (LOC) less than 12% by volume; a specific test is required in order to determine this concentration.

However, although attractive, this solution is often expensive, as the quantity of gas required may be considerable in large areas. It is also essential to ensure that the installations concerned are gas-tight.

Moreover, if it is to be effective, the method requires strict monitoring of control and working procedures so as to guarantee a constant O_2 content inferior to the LOC.

For all these reasons, rendering the atmosphere inert can only be justified when the economics of the method are advantageous in respect of product quality (dehydrated products) and in critical situations where there is a major explosion hazard (cell overheating and self-ignition).

Thus, reducing the possibility of a dust explosion is essentially a matter of controlling the formation of explosive atmospheres and eliminating the effective ignition sources by selecting the appropriate equipment and materials; at the same time, proper maintenance and control procedures need to be introduced and all the appropriate safety procedures and instructions observed.

4.9.2 Protection

Very often, preventive measures are not sufficient to reduce the risk of explosion to an acceptable level; thus, the actual consequences related to pressure, temperature and dangerous release effects have to be considered if they are to be minimized.

With equipment or areas where dust is permanently or semipermanently in suspension at explosive concentrations, there is always the possibility of a primary explosion and protective measures should be installed to limit its effects. Primary explosions, if not properly reduced, can cause dust to go back in suspension and so increase the possibility of a secondary explosion, with correspondingly more destructive results.

In addition to the preventive measures mentioned, protective measures should be taken with the purpose of reducing the effects of an explosion.

Several types of measures may be distinguished, depending on whether they are designed to protect against excess pressure or against propagation of explosion.

The methods used for protection against explosion pressure are

- pressure resistance: buildings and equipment,
- reduction of the maximum explosion pressure (venting),
- explosion suppression by flame extinguishing.

The avoidance of propagation of the explosion may be obtained by

- isolating the various installations (isolating devices),
- using barriers.

4.9.2.1 Pressure-Resistant Buildings and Equipment

The method here consists in ensuring that those parts of the buildings and equipment likely to be affected by pressure effects induced by an explosion are sufficiently resistant and not liable to collapse or to be blown out.

To achieve this, the strength of the different structures should be greater than the maximum explosion pressure. The possibility of a detonation should be dealt with.

This is comparatively easy with isolated equipment of fairly small size and not elongated volume, as estimations of the maximum pressure to be expected are reliable and give values of less than 10 bar, compatible with industrially and economically viable installations.

In the case of a number of connected installations, it is difficult to assess the maximum possible pressure, which may under certain conditions reach very high levels (50 bar), which complicates the use of this protective technique.

Thus, designing installations able to resist explosion pressure concerns basically small enclosed areas (equipment rather than buildings) and small-diameter ducts (e.g., for pneumatic conveying).

4.9.2.2 Reduction of the Maximum Explosion Pressure (Venting)

The method here consists in "explosion relief," so that the pressure reached (reduced explosion pressure) is clearly inferior to the strength of those parts of the installation likely to be exposed to the pressure effects induced by an explosion.

With equipment or buildings that are not very long, reduction of the pressure caused by an explosion can be achieved by means of relief vents.

The size of the vents depends mainly on the reduced explosion pressure that the enclosure can withstand, the severity of the explosion and the opening pressure and inertia of the device used.

A number of methods can be used to calculate vent surfaces, among others the nomograms mentioned in the NFP A 68 "Explosion Venting" guide.

Protection of small enclosed areas (less than 100 m^3), such as those for equipment (e.g., filters, small silos, etc.), can be ensured by explosion vents consisting of panels made of some light material; these open as soon as the excess pressure exceeds a threshold value (opening or bursting pressure) worked out according to the type of vent.

Two types of vents are possible: either bursting disks (which can only be used once) or explosion doors (re-usable following an explosion).

Explosion doors, whose chief feature is that they close automatically as soon as the excess pressure level is right, have the advantage of avoiding air ingress in the enclosure and a further fire development. Moreover, the toxic gas emissions formed by an explosion are therefore avoided.

When large volumes have to be protected, for example buildings or large silos, part of the outer walls and roof may be used for venting. Debris can be blown out in this situation.

Note: blast and flame effects act at the outlet of the relief holes; in the case of dust layers outside the equipment being protected, this can lead, after raising of dust, to a secondary explosion.

It is therefore essential that venting should be effected in a direction which does not expose the personnel or any other equipment to any danger, preferably towards the outside of the building.

In the event of a dust explosion, it should be remembered that with explosive atmosphere volumes of about 20 m^3, flames of up to 10 m can escape into the air.

With equipment whose length/diameter is greater than 5, protection by venting is inadvisable, as opening the vent may increase the flames.

4.9.2.3 Explosion Suppression by Flame Extinguishing

With this method, prevention of an explosion is achieved by flame extinguishing, by means of dispersing an extinguishing substance in the reactive mixture.

An explosion must be detected as soon as possible after it occurs, in order to limit its effects before it does really serious damage.

Suppression systems consist of a detector, which reacts very quickly (within a few milliseconds) and one or more fast-acting extinguishers which act within tens of milliseconds according to the size of the vessels.

This method is recommended for the protection of installations in cases where venting would not be appropriate, such as for example where high-speed flames propagating in a duct can emerge in equipment.

It may also be suitable under certain conditions for protecting volumes such as silos; however, in the case of very large volumes, and when the products are highly reactive, a special study would be required.

At all events, requirements (such as the extinguishing substance amount, the number and positions of extinguishers and the positions of the detectors) must be adapted to the installation to be protected, and should also take into account the effectiveness and general performance of the equipment to be used.

4.9.2.4 **Isolating the Various Installations (Isolating Devices)**

The principle here consists in restricting the explosion to a single installation, or even to just one part of an installation, in order to prevent it from affecting adjacent installations.

To do this, the blaze can be halted by a completely or partially flame-resistant device.

Given the principle involved, this method is generally restricted to the protection of pipe work of relatively small diameters (300–500 mm).

If the pipe work is closed off (for example with a rotary valve), the protective device and the pipe work should be able to withstand the effects of excess pressure (on the order of 10 bar).

If the pipe work is equipped with flame arresters, the gases released by the explosion are cooled, the flame disappears at the outlet of the device and the effects of the explosion are practically all withstood by the protective device, which should therefore ensure adequate resistance.

4.9.2.5 **Operation of Protective System**

Protection against the effects of an explosion is a question of installing the right equipment, intended either to limit the effects of explosion pressure or to limit flame propagation.

To be effective, the equipment used should be

- appropriate to the installation to be protected,
- tested under actual conditions of an explosion,
- installed in accordance with current practice and with the type of installation to be protected and depending on the performance of the equipment envisaged,
- able to withstand the operating environment in which it will be required to function (dust, shocks, vibrations, etc.),
- easy to maintain in working order,

- maintained by qualified personnel in accordance with current control and maintenance procedures.

Any use of potentially unreliable protective equipment may be banned, as it will induce a false sense of safety in respect of hazards.

4.10 Fire

Eliminating one or more of the conditions included in the "pentagon of explosion" does not necessarily prevent the occurrence of a fire, which in fact requires the elimination of one of the elements in the "fire triangle." That is why there are a large number of cases where, when an incident comes to be analyzed, a fire has followed a dust explosion.

And, whilst a fire may follow an explosion, at the same time an explosion may result from a fire that has got out of control.

In installations or with equipment, the potential risks of an outbreak of fire are the result of the simultaneous presence of combustible products or materials in air and sufficiently intense sources of heat.

Thus, if a storage of any pulverulent combustible product catches fire, it is started either internally by a process of self-ignition or by an external source of ignition. Such sources can also induce the combustion of combustible materials, of inherent parts of equipment and buildings and of stored flammable liquids.

4.10.1 Prevention

For a fire to start, three conditions need to be present simultaneously – the "fire triangle:"

- a combustible element,
- an ignition source,
- an oxidizer.

To prevent a fire, action can therefore be taken as regards the combustible elements and sources of ignition, to reduce the probability of occurrence of fire.

4.10.1.1 Combustible Elements

Combustible elements liable to contribute to an outbreak of fire may be either the agro, feed and food products being stored or combustible materials required for operating purposes (conveyor belt, oil, fuel, etc.) found within the installation or stored in the vicinity or in special areas.

With stored products, fire prevention must take into account the particular characteristics of the products in respect of fire. For the different types of operation carried out in the silo, the following actions need to be taken:

- avoid unnecessary accumulations of products immediately adjacent to areas where there is a high risk of ignition (drying circuit, thermal engines, electric motors without protective measures, conveyors, etc.),
- ensure that products are maintained in a state such as to limit the risk of self-ignition (humidity/temperature) in cells and dryers.

With other combustible products present in the silo and equipment, fire prevention consists of the following:

- the use of non-combustible or difficult to ignite materials,
- limiting the quantities to be stored to a strict minimum in the vicinity of product storage areas (oil, solvents, compressed gas, etc.).

4.10.1.2 **Ignition Sources**

The same sources of ignition are found for both fires and explosions. Observations on the origins of ignition sources made in the section dealing with the prevention of explosions generally apply equally well to fire.

Within these sources, a very close watch needs to be kept on ignition following self-heating, as a fire can occur without any outside heat, the heat level causing ignition being generated inside the installation, even at ambient temperature.

The self-heating of stored matter does not proceed in its whole volume but only in some places with optimum conditions related to sufficient heat accumulation. These places are always inside the material. Generally, the hazard is evident only in the developed stage of the self-ignition.

To the self-ignition symptoms belong

(1) the pressing down of products,
(2) strong exudation,
(3) an odor like fermentation.

The measuring of the temperature is therefore necessary. In the closed volume of silos the temperatures and/or concentrations of the gaseous products of fermentation are to be monitored.

In order to eliminate external effective ignition sources and reduce the risk of fire, preventive measures have to be taken, measures appropriate both to the type of ignition sources liable to occur and to the characteristics of the products concerned. These measures are chiefly a matter of the following:

- choice of installations and of the materials to be used,
- design and functional characteristics of the installations,
- appropriate safety control and monitoring measures.

In order to reduce the risk of an outbreak of fire and ensure an adequate safety level, preventive measures shall also include the safe separation of combustibles from ignition sources. Additionally, rules for the use, monitoring and maintenance of the storage installations concerned must be applied.

4.10.2 Protection

In spite of active prevention measures kept, there exist possibilities of fire spreading. The sooner the fire is detected, controlled and extinguished, the smaller the losses. At assessment of a possibility of a fire spreading it is necessary to take into consideration the characteristics of the combustible construction material, and their spatial distribution (fire load, fire resistance, reaction to fire); the fire parameters of combustible substances must also be determined (combustibility, flame spread rate, heat release rate, linear burning rate, etc.) under both normal working conditions and under the unusual working conditions to be expected. It is, at the same time, necessary not to forget a potential explosion which enables usually further wide fire spreading. Fire spreading can also be limited by means of an early and effective fire fighting intervention.

Last, but not least, a safe evacuation of people shall be ensured.

The spread of the fire is given by properties, amount and arrangement of the combustible and by a possibility of heat transfer during fire. In a fire there are temperatures of 700–1200 °C. Heat transfer proceeds mainly through convection. The flowing of combustion gases can be influenced by means of smoke flaps. The flowing of combustion gases carries also the burning particles which enable the fire to transfer to greater distance. At burning through of an external construction the influence of wind will manifest. The spread of a fire in a building can be influenced especially by means of measures of fire prevention of buildings. The basic philosophy of fire prevention is to divide a building into compartments by means of fire compartmentalization (fire walls, ceilings, screens, peripheral walls) whose function is to hinder the spread of a fire to adjacent buildings and equipment.

By means of fire compartments the escape routes, evacuation lifts, installation ducts and shafts, machine rooms of lifts and ventilation, boiler rooms, storage rooms for fuel, distributions of high and low voltages must be protected. The protection is also recommended for rooms with explosion and toxicity hazard and for rooms containing combustible liquids. It is necessary to divide other rooms into fire compartments so that

- the escape of persons from each fire compartment would be possible – the access of fire units would be secured,
- the combustion gas control would be possible.

The limited dimensions (sizes) of fire compartments, that is the greatest length and width, will be determined in dependence on fire load, mass burning rate of substances, height position of fire compartment and on the type of construction.

Structural (constructional) elements can cause the fire intensity to be non-increasing. Buildings are then classified as buildings from non-combustible structures, miscellaneous and combustible structures.

A fire safety degree is fulfilled if all structural (constructional) elements comply with required reaction to fire and fire resistance.

The limited dimension (size) of a fire compartment can be also influenced by fire equipment. Keeping safety distance is a very important measure. Heat radiation of $3\,kW\,m^{-2}$ for the beginning of irreversible effects on man and of $5\,kW\,m^{-2}$ for the beginning of lethal effects are to be considered.

The designing of fire shutters of connecting openings is a very important problem. The shutters are divided into

- preventing spread of heat,
- limiting spread of heat,
- tightness against smoke penetration.

With agro, feed and food product storage, the most potentially serious fires are those liable to occur in one or even several storage bins. Additionally, the risk of an explosion following this type of fire cannot be excluded.

To ensure early and efficient intervention

It is possible to divide a fire into several time periods:

- first phase – from fire occurrence to its observation,
- second phase – from observation to fire registration,
- third phase – from registration to the raise of alarm for fire unit,
- fourth phase – from the raise of alarm to the beginning of fire intervention.

The reducing of each phase is a very important measure against the propagation of fire.

Technical possibilities for reducing it are as follows:

- fire detection and alarm system – it reduces the first and second phases,
- fire detection with an automatic raise of alarm – it reduces the first, second and third phases,
- fixed extinguishing system – it reduces the first, second, third and fourth phases.

Further, it is necessary to solve the following problems:

- to ensure an access to the place of fire occurrence (fire focus) – accessible places, keeping free routes and ensuring practicability of roads for fire vehicles,
- to ensure an access to the position of water supply,
- to select correctly extinguishing agents:
    - for a starting fire,
    - for a fully developed fire,

Note: the selection of the quantity of the extinguishing agent to be used depends on the kind of combustible substance and on the possibilities of the spread of fire.

- to ensure storage of the extinguishing agent,
- to propose and secure fire extinguishing equipment with fixed (with automatic or manual control) or hand-operated fire extinguishers (capability – training of persons),
- to propose and ensure the availability of fire unit (type, number, equipment, details for intervention, conditions for raise of alarm, training).

According to the extinguishing agent used the fixed extinguishing systems are divided into

a. water – sprinkler or drencher systems,
b. foam system,
c. inert gas system,
d. powder system,
e. halon system.

It must be pointed out that water spraying systems (deluge and sprinklers) are able to cool the equipment and building walls, but are totally ineffective on smoldering or glowing fires.

The injection of large amounts of inert gas through the entire mass of self-heated or self-ignited material is the only efficient way to fight against such an event (cooling off).

Generally, it is also an absolute pre-requisite to use fire fighting systems, the efficiency of which has been proven.

To ensure evacuation of people

For evacuation it is necessary to project escape routes. Escape routes can be: unprotected, protected partly and protected. Protected escape routes are divided according to ventilation modes. In a first type, the route is separated from other fire compartments by means of fire shutters or openings and this type ventilates

a. through a natural ventilation,
b. through a forced ventilation.

The route of a second type could be the installation of a separately ventilated hallway (small vestibule) which enables a safe stay of persons during evacuation.

The route of the third type does not structurally differ from the second one. Only the ventilation mode makes a difference. Spaces of the route of the third type must be equipped by means of forced overpressure ventilation including a hallway (small vestibule) against smoke penetration.

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5
Fire Detection

Ralf Schäckel and translated by Ulrich Krause

5.1
Introduction

Fire is a common part of our life. From the early childhood on everybody learns to respect the two sides of a fire. Fire can give us comfort and wellness if it burns in a controlled way. Fire can also cause fear and fright when it runs out of control.

How can a fire raise up? Firstly, a flammable material must be present, for example paper. Secondly, oxygen is necessary, which is available in the ambient air. Thirdly, heat has to be transmitted to the flammable material to start a combustion process. A newspaper will not start to burn when laying at home on the table.

I myself – as a youngster – ignited a newspaper by focusing sunlight with a reading glass of my grandpa. After he discovered my experiment, I got some "explanation" on the hazards of my attitude to this kind of experiment and was deprived of the lenses and the experimental tools.

But what were my findings? Before the paper started to burn I observed a more or less intense development of smoke. After a while the first flames occurred. Their light was not very bright, but enough to see it in the sunlight.

And finally I burnt my fingers when I tried to extinguish the flame though the pieces of paper were only small. Fortunately nothing serious happened, only the smell of the fire betrayed me. What were the consequences: see above.

In principle, I learnt as a child the three characteristics of a fire. During combustion substances are generated which you can see. Furthermore, light is emitted which you can see. And, finally, heat is produced which you can feel. All three characteristics appear in a fire with variable intensity depending on the material and on the stage of the fire.

This offers us three possibilities to automatically detect a fire and after this to alert somebody.

The European standard EN 54-1 [1] discriminates the following detectors for a fire in the way quoted here:

"Fire detectors may be differentiated in several ways. These may include

- the phenomenon detected . . .,
- the way in which the detector responds to the phenomenon detected . . .,

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- the configuration of the detector . . .,
- the resettability of the detector . . .,
- the detachability of the detector . . .,
- the type of signal transmitted . . .;" see Ref. [1].

Since the present book deals with silos, this standard is not mandatory. However, we should not ignore the experiences made with fire detection in buildings. There are various possibilities to choose detection systems which are suitable to detect fires in silos based on EN 54. The knowledge of the technical framework for the certification of fire alarm systems after EN 54 is helpful for assessing the suitability for the respective application.

Which types of automated fire alarm systems can be applied?

Independently of the type of the automated fire alarm, the following principles have to be considered.

Fire alarm systems have to be built in in such a way that they are easily accessible. Each alarm system is in need of inspection in certain periods of time. This has to be considered as well when fixing the position for building in.

Each detector is in need of regular inspection and maintenance. This has to be considered as well when deciding about the position at which the detector is installed. Fire alarms without or with poor maintenance are a very high hazard. Each fire safety concept is based on properly working fire alarms.

5.2 Smoke Detectors

5.2.1 General

Optical smoke detectors and ionization smoke detectors are triggered by the products of a combustion or pyrolysis contained in the air. Therefore, these details are especially suitable when in the early stage of a developing fire smoke is generated. The specific properties of the smoke (smoke color, size of smoke particles) should be taken into account when selecting a specific type of smoke sensor.

Optical smoke detectors detect comparatively large smoke particles as they occur in the early stage of a fire (smoldering). Ionization smoke detectors detect smaller particles in the smoke as they occur in the stage of a fire immediately before transition to flaming takes place.

When making a decision for the selection of appropriate detectors it has to be considered if the fire is likely to start as smoldering or quickly turns into a flaming fire.

5.2.2 Optical Smoke Detectors

This type of detector consists of an optical device making use of the scattering of light by smoke particles. A single-chamber method and a double-chamber method

are available. In the single-chamber method an alert signal is emitted when a previously adjusted threshold is reached. In the double-chamber method one chamber is used as a measuring chamber, the other as a reference chamber. The smoke penetrates the measuring chamber. An alert signal is emitted when the output signal from the measuring chamber deviates from that of the reference chamber.

5.2.3
Ionization Smoke Detectors

This type of system consists of two radiation sources of extremely low intensity which cause an ionization of the air in a measuring chamber and a reference chamber. Smoke penetrating into the measuring chamber alters the ionization process. This alteration compared to the reference chamber is transformed into an alert signal when a certain threshold value is reached.

5.2.4
Fire Gas Detectors

This type of fire detector is not standardized in Europe and is not even mentioned in EN 54. Nevertheless, these detectors are very suitable for industrial applications, especially in dust-loaded areas.

Fire gas detectors consist of semiconductor sensors which are suitable for the analysis of gas mixtures. These sensor elements do not react to smoke particles but instead to variations in the gas composition caused by a starting fire.

By applying multiple sensors of different sensitivity within one detector it is possible to detect different gases. The semiconducting sensors are protected by a sintered cap. The gas diffuses through the sintered cap to the sensitive layers. Dust or dirt on the sintered cap cannot prevent the diffusion. Besides, the fire gas detectors are not sensitive against fog.

An analysis of the different output signals of the semiconductor sensors allows an identification of different types of fires. An individual adoption to the application in question is possible as well as the suppression of background "noise." An example of a fire gas detector is given in Figure 5.1, while Figure 5.2 shows a detector of the same type in a "real-life" application.

The spectrum of industrial applications ranges from supervision of coal storage silos to agricultural products, wood, sawdust, paper, straw pellets and biomass to recycling materials.

5.3
Flame Detectors

The standard EN 54-1 [1] defines a flame detector as follows:

> *"A detector which responds to the radiation emitted by the flames from a fire."*

Figure 5.1 Fire gas detector ADICOS GSME (Courtesy GreCon GmbH).

Flames emit ultraviolet, visible and infrared spectra of radiation. Flame detectors contain optical sensors for these spectra. Flames emit these spectral radiations, however, not with constant intensity, but with a certain pattern of emissivity, the so-called jitter frequency.

The evaluation of the jitter frequency serves as additional information for an ascertained identification of the stage of alert.

Being optical sensors, flame detectors need certain conditions for a reliable detection of a fire. Smoke impedes the transmission of ultraviolet, visible and

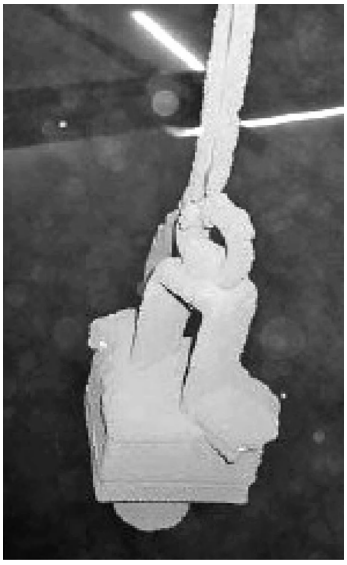

Figure 5.2 Fire gas detector ADICOS GSME in an industrial application (courtesy GreCon GmbH).

Figure 5.3 Flame detector (courtesy GreCon GmbH).

infrared radiation. Therefore, flame detectors should be applied for fires with fast transition to flaming only. Shadows caused by obstructions in the supervised area hamper the early flame detection.

Dust or other layers on the optical part of the flame detector also reduce the intensity of the radiation emitted by a flame. Therefore, many flame detectors have a control system for the degree of extinction. If the dirt on the optical part exceeds a previously adjusted threshold an alert signal is triggered.

VIS flame detectors work in the visible range of the spectrum. Therefore, these detectors are applied in a dark environment only. The alert signal is emitted when the jitter frequency is reached.

IR flame detectors use the infrared spectrum. Special filters in front of the sensors prevent the transmission of other fractions of spectral radiation. The alert signal is also given when the jitter frequency is reached.

UV flame detectors work in the ultraviolet spectrum. Special glass windows are necessary to align the transmission of the UV light to the sensor. Acrylic glass or normal window glass cause a strong extinction of the UV radiation. Such obstructions have to be removed from the pathway between flame and detector. Alternatively, they can be replaced by other materials. The alert signal is emitted when the jitter frequency is reached.

The flame detectors are available in different designs, for example as UV and IR detectors as two separate units in one casing (Figure 5.3). By this the probability of false alarms can be reduced considerably. The same applies to flame detectors with three sensing systems. The goals are the improvement of functional reliability and the reduction of false alarms. When selecting a specific type of detector, possible sources of disturbance and false alarms have to be considered.

5.4
Spark Detectors

For this type of detector there is no standard available in Europe. EN 54 does not even mention this type of detector. Nevertheless, these detectors are very useful in industrial applications, especially in a dusty environment.

Spark detectors enable an early recognition of ignition sources before a fire breaks out. They are implemented in pneumatic conveying systems and in drop towers. All types of detectors mentioned previously (smoke detectors, fire gas detectors, flame detectors and temperature sensors as described below) need the fire itself – though at different stages of development – to generate a signal. In contrast to this, spark detectors are optically highly sensitive detectors for an ascertained notification of the smallest ignition sources in flows of material. Spark detectors are always integrated into a project-specific spark extinction system. Such a tuned safety system is based on the following functional principle.

The spark detector detects a spark or hot material when passing a pneumatic conveying system. A very rapid water extinguisher is triggered within 10 ms maximum. The water extinguisher is located at a project-specific distance from the detector in the flow direction. This water extinction system consists of closing blades, dirt collectors, magnetic valve, flow or pressure controller, injection nozzles, ducting and if necessary a heater. It is designed in such a way that the entire diameter of the conveying pipe can be filled with water mist efficient enough for extinction in an extremely short time. The sparks or the hot parts together with the flow of material pass through the water mist and are extinguished safely (Figure 5.4).

The water mist is maintained for an adjustable span of time. Provided that no further sparks or hot parts are detected, the extinction procedure is finished after the adjusted time. Every further spark or hot part contained in the flow of material prolongs the extinction time.

Spark extinction systems have been state of the art for many years in industrial installations of the woodworking industry. Similar protection concepts have been applied in the sugar, cocoa, coffee and textile industries. In Germany there exists a guideline of the VdS (Association of Loss Insurers) for spark detection, spark elimination and extinction systems: "Design and installation" under the registration number VdS 2106 (state 05/2003).

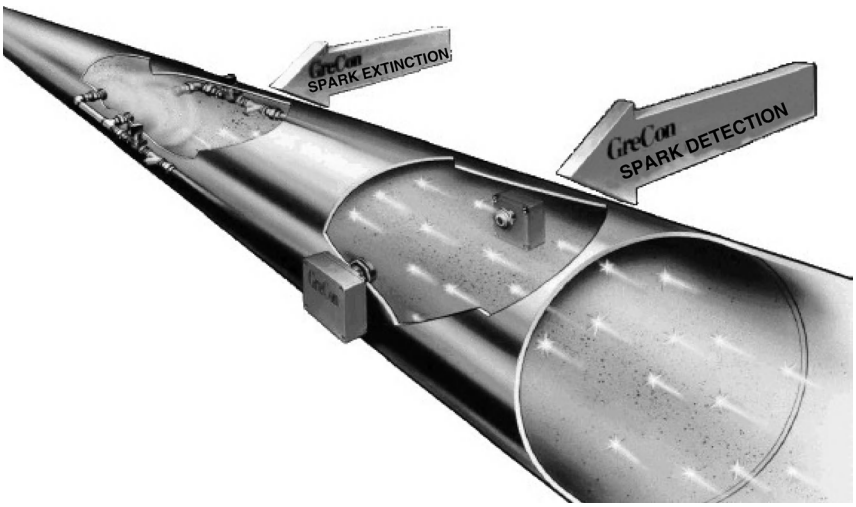

Figure 5.4 Spark detector combined with extinction system (courtesy GreCon Gmbh).

Figure 5.5 Daylight-sensitive spark detectors (courtesy GreCon GmbH).

Spark detectors contain optical sensors which work in the infrared spectrum of radiation. They recognize sparks or hot material in flows of products also at elevated temperatures of the conveyed material. For product temperatures up to 350 °C special spark detectors with light-transmission cables are available. Two kinds of sensors can be distinguished: daylight-sensitive and daylight-insensitive spark detectors.

5.4.1
Daylight-Sensitive Spark Detectors

This type of sensor operates in the infrared spectrum at a wavelength of 700 nm–1.1 m above the visible light. They are suitable to detect even the smallest sparks in flows of material. They need complete darkness for a safe functionality. External light leads to an immediate alert (Figure 5.5).

5.4.2
Daylight-Insensitive Spark Detectors

Daylight-insensitive sensors operate in the infrared spectrum at a wavelength between 3.5 and 4.5 µm above the visible light. Optical filters are mounted to the sensor to filter the visible portion of radiation. This type of detector is especially suitable to recognize hot material from a surface temperature of about 100 °C on.

Dust impedes the transmission of radiation in the above-mentioned range of the spectrum. Therefore, a minimum of dust is allowed only for a reliable operation of these sensors (Figure 5.6).

5.5
Heat Detectors

In the European standard EN 54-1 [1] the following definition for heat detectors is given:

Figure 5.6 Daylight-insensitive spark detectors (courtesy GreCon GmbH).

"A detector which responds to an increase in temperature."

Heat detectors can be differentiated according to two working principles:

1. Maximum heat detectors: these detectors react to an excess of a previously adjusted threshold temperature over a certain range of time depending on the thermal inertia of the sensors.
2. Differential heat sensors: for this type of sensor the alarm is triggered by a rise of temperature over time occurring within the range covered by the supervision.

Some heat sensors combine both measuring principles (Figure 5.7).

What types of non-automated fire detectors may be applied?

Hand-operated fire detectors or manual button operated fire alarm systems are non-automated systems. With respect to their function the casing is in bright color. The triggering element (buzzer) is placed behind a glass window. The

Figure 5.7 Heat detector (left: front view, right: rear view, courtesy GreCon GmbH).

window has to be destroyed to operate the buzzer. The glass window prevents an unintentional operation. If for example a silo is equipped with an automated extinction system, it may be worth considering triggering the extinction by such a manually operated alarm in visual distance of the silo. Apart from the attractiveness to automate this kind of system, a manual operation may be a very sensible means to minimize incidents.

5.6 Application Examples

5.6.1 Fire Protection Silo in a Fiber Board Factory

Fire protection silos in fiber board factories are used for temporary storage after drying to minimize the fire hazard in subsequent process steps. In addition, when operated in a controlled manner during filling and emptying, they can also be used for the purpose of explosion isolation between dryer and sieves.

The wood chips are conveyed into the silo via different transportation sections and parts of equipment. Each of these sections is supervised by spark detectors depending on its properties, thus forming a multistep protection concept of the entire transportation pathway from the drier to the silo. However, these preceding sections are not discussed in the following. The following flow sheet, Figure 5.8 covers the protection of the silo entry and the pathway behind the silo discharge unit. An up-to-date fiber board factory contains up to 100 spark detection and extinction units.

In the example in Figure 5.8 the wood chips can enter the silo via three conveying lines. Each of these lines is protected by spark detectors and extinguishers. If one of

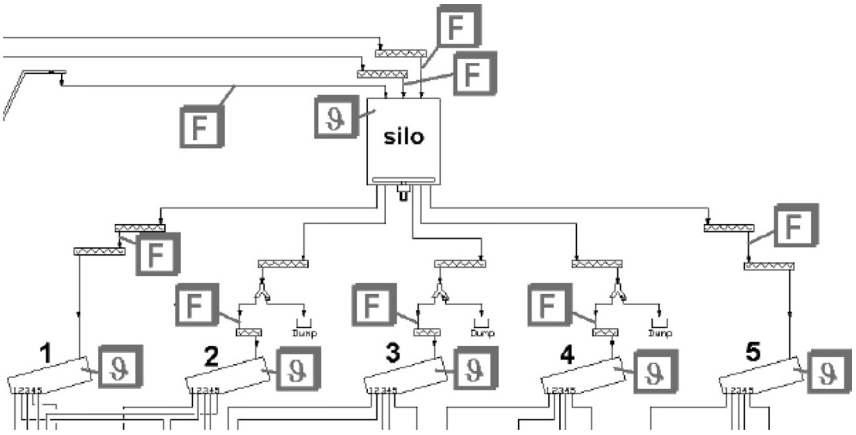

Figure 5.8 Spark detectors (F) and temperature sensors (θ) in a fiber board production line.

the spark detectors gives an alarm signal, the water extinguisher is activated over the extinction time and the sparks or the hot material parts are extinguished.

The amount of water injected is not a problem for the production process. Fire protection silos have volumes of up to several hundreds of cubic meters. Injecting, for example, 10 L of water is not relevant. The residence time of the wood chips in the silo is normally in the range of hours.

The silo in the present example has five discharge openings. Each of these discharges leads onto a screw conveyor. (The screw conveyors have diverters in the conveying way. These conveyors are not discussed here.)

Each of the screw conveyors is followed by a second screw conveyor. The wood chips drop from the first conveyor onto the second conveyor by gravity. The freely falling material is scanned by a spark detector connected to a water extinguisher. These detectors activate the water extinguisher for a time of five seconds if sparks are detected.

From the second conveyor the wood chips drop onto a sieving machine. This sieve is supervised by a temperature alarm unit.

Why are two subsequent screw conveyors used instead of one?

The transportation from the conveyors to the sieving machine cannot be designed without daylight transmission. Therefore, the application of daylight-sensitive detectors, which react highly sensitively to the beginning of the smallest ignition, is not possible. In contrast to this, the section between two screw conveyors can be designed absolutely dark. This allows an optimal supervision of the flow of material with respect to ignition sources conveyed out of the fire protection silo.

Which conclusion can be drawn from this example?

With respect to a maximum level of safety it may become necessary to redesign a technical process in such a way that the most suitable safety components are applied in an optimal environment for their function. Finding such solutions is only possible by an intense communication between purchaser and deliverer of such a system.

Why has the discharge of a fire protection silo to be supervised although all filling openings are equipped with detection and extinction systems?

Under practical conditions it has been observed that hidden glowing nests can migrate. Such glowing nests may also be generated in a fire protection storage silo over a longer span of time. Especially when the production process is discontinuous such incidents can occur. Also, unpredictable events may trigger hazardous situations. Practice is always more multifaceted than all foreseeable scenarios.

The temperature sensors mounted to the roof of the fire protection silo are meant to warn of an increase of the internal temperature of the silo. This is done using a two-step concept.

Temperature sensors with two different thresholds are used. The lower threshold gives a warning signal. The operator can respond to it with safety actions. The higher threshold is an alarm. If appropriate, a manual extinction of the silo fire can be undertaken.

What is the meaning of the diverter in the three conveying pathways in the middle?

In the case of long-time appearance of sparks at one or several of the discharge openings, a hidden fire or glowing nest may have occurred in the silo. Using the diverters the silo can be emptied safely provided that the other safety measures are considered as well.

5.6.2
Recycling of Metal Parts, for example Car Residues

Suppose that a shredder for metal scrap, for example parts removed from cars, is equipped with an open belt conveyor feeding into a silo. During the process of size reduction the metal parts heat up considerably. Local heat generation is, however, mitigated along the belt conveyor and normally not a hazard during storage of the shredded metal. If residues of oil or petrol adhere to the metal a fast ignition followed by an open flame may occur. The aim of the present application is to prevent the entrance of burning parts of the metal scrap into the silo.

It makes no sense to use spark detectors in this application because this type of detector is also triggered by the hot metal parts. Therefore, a UV/IR flame detector was applied. The flame detector is positioned immediately behind the discharge opening of the shredder. This guarantees an early detection of open flames.

During an alarm of the flame detector an automated water extinguisher is triggered covering the entire length of the belt conveyor. The water extinguisher kills the fire and at the same time cools down the other hot metal parts.

The flame detector has been proven to notice fires reliably and – because of the separate UV and IR signal channels – the probability of false alarms is very low. A sketch of this solution is shown in Figure 5.9.

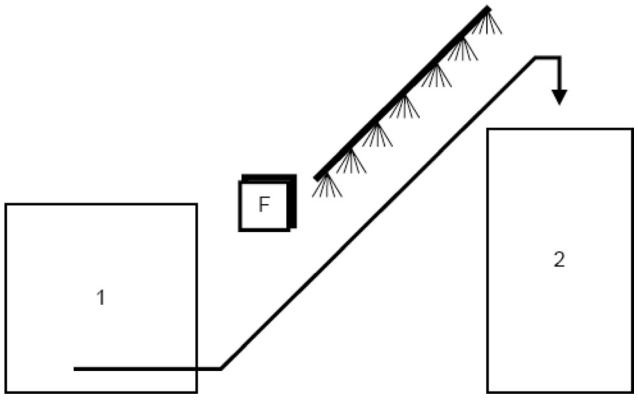

Figure 5.9 Application of a flame detector (F) and an extinguishing system between shredder (1) and silo (2) in a car recycling plant.

5.6.3
Feeding Line of a Silo Plant with 24 Silo Cells

A silo plant for grain has 24 silo cells. The supply of the grain to the individual cells is done by a mechanical distribution system above the silo cells. The feeding system is nearly completely covered and by this forms a confined volume.

The central feeding line of the material flow into the distributor is supervised by spark detectors. When the spark detectors give an alarm signal an automated water extinguisher is triggered and the ignited material is safely extinguished.

Within the distributing system there exist further transmission points where the material drops from the first conveyor to the second by gravity. Each of these transmission points is equipped with spark detectors and automated water extinguishers. As soon as one of the spark detectors is initiated it activates the corresponding water extinguisher.

Each of the individual silo cells has a discharge opening which ends in a central transportation system. The first drop point of this transportation system is also equipped with spark detectors and automated water extinguishers using the same safety principles as at the silo feeder.

Why are additional smoke detectors installed at the silo feeder, as visible from Figure 5.10?

What is their meaning with respect to safety?

There is always the hazard of conveying hidden glowing nests into the silo. Hidden glowing nests are agglomerations of material with surface temperatures not much different from the temperature of the unreacted material. In the center of these agglomerations, however, the temperature is much higher. Eventually the material is even glowing. The outer shell surrounding the glowing kernel acts as a thermal

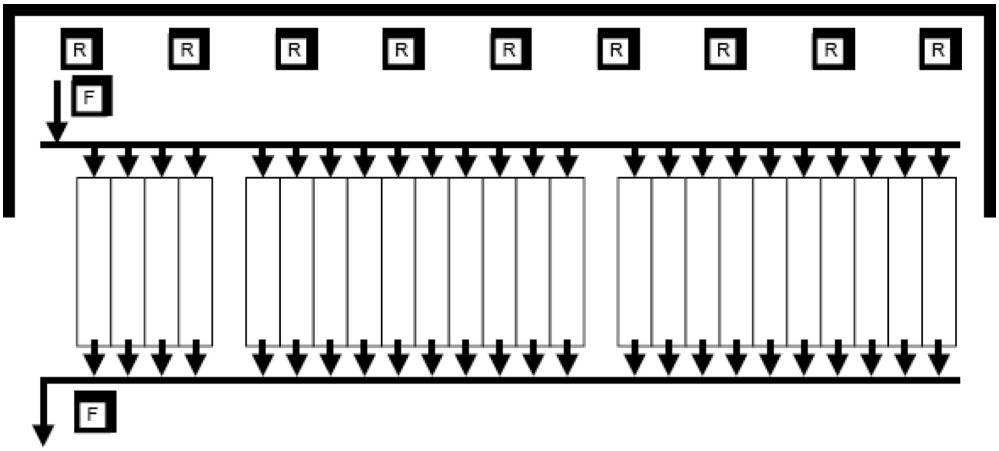

Figure 5.10 Application of spark detectors (F) and smoke detectors (R) in a grain silo plant consisting of 24 silo cells.

insulation. Spark detectors or temperature sensors cannot reveal the hidden glowing nest.

During dropping down the glowing nests eventually disintegrate by crashing on the bottom. The spark detectors will then be able to detect the glowing kernel.

In the case where the glowing nests keep their integrity they possibly release smoke. This smoke is characteristic for an early stage of the fire. The smoke detectors are installed to detect such hidden glowing nests which release smoke and to trigger an alarm. When the smoke alarm is activated the operator is informed. He then has to inspect the equipment on site and has to respond to the alarm.

If two adjacent smoke detectors are activated at the same time, the automatic water extinguisher is activated which is kept in operation until it is reset manually by the operator.

Smoke detectors have to be installed at a position which is easily accessible. Due to the dropping of particles elutriation of dust can hardly be avoided. In a practical application the following situation was found: the detector located nearest to the supply of material gave most frequently false alarms due to the load of dust while the second nearest showed much fewer false alarms. All other detectors had to be inspected twice a year only. By management measures the inspection intervals of the first and the second detectors were adapted to the operational conditions. With respect to maximum safety the higher effort was accepted.

5.6.4
Silo of a Biomass Power Station

After unloading the material is conveyed by mechanical conveyors to a disk separator. Spark detectors are mounted behind the drop point between the discharge of the conveyor and the disk separator. The spark detectors are designed to notice surface

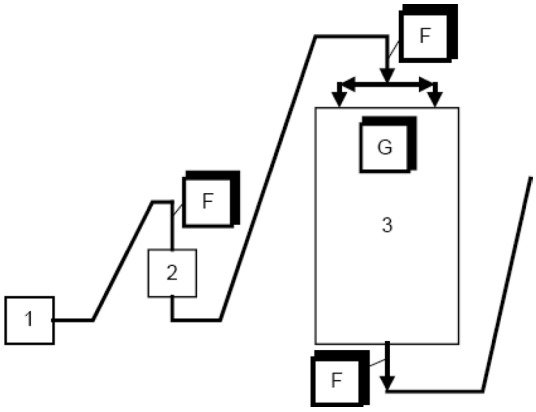

Figure 5.11 Protection of a biomass silo plant with spark detectors (F) and fire gas sensors (G) between the charging funnel (1), the disk separator (2) and the silo (3).

temperatures from 250 °C on. The material eventually burning is extinguished with water automatically as soon as the spark detectors give an alarm. The flow of the material is however not interrupted.

After the disk separator the flux of material is transported onto a distributor above the silo. The silo has a diameter of 23 m and a height of 26 m and is made of steel-reinforced concrete.

Inside the disk separator, between conveyor and distributor, spark detectors are mounted to supervise the material flux for ignited parts of material. These spark detectors also give an alarm at a surface temperature of 250 °C. In the case of an alarm the distributor is shut down to prevent the intrusion of ignited material into the silo.

Additional spark detectors are mounted to the discharge duct of the silo to protect the subsequent parts of the equipment. In the case where hot particles are observed by the spark detectors the conveyor is stopped.

Fire detectors are mounted to the silo ceiling to detect a fire as early as possible. The stored material allows an unimpeded gas diffusion; hence, gas detection can be used as the detection method. The fire detectors have to be certified for use in explosible atmosphere since the inside of the silo is zone 21, according to the definition of zones of explosive atmosphere following the European standard EN 1127–1.

Fire detectors are able to notice fires very early. This allows sufficient time for the personnel to react. The principle is depicted in Figure 5.11.

References

1 DIN EN 54-1 (1996) *Fire Detection and Fire Alarm Systems*, Beuth Verlag, Berlin.

6
Case Studies

David Westermann and Rolf Eckhoff

This chapter comprises some case studies of fires which occurred in large silos storing flammable organic materials like wood pellets, animal feed, grain or sugar. All cases have in common that large masses of material were involved, the fires were discovered at a relatively late stage and fire fighting was very difficult and time consuming. The studies in this chapter are therefore first of all intended as "lessons to learn" with respect to

- fire prevention,
- fire detection,
- selection of appropriate means for fire protection,
- preparation of the local fire fighting units to the case of a possible fire on a specific site.

6.1
Fire in a Silo for Wood Pellets in Esbjerg, Denmark, 1998–1999

David Westermann

6.1.1
Summary

On 5 November 1998, the owners of a silo building situated in the harbor area in Esbjerg, Denmark sent a request to the local rescue company for technical assistance. There was an unpleasant smell in the area and they suspected a fire in a silo cell.

The silo building was 85 m high and comprised 23 cells, each with a capacity of 2300 m^3. Seventeen of the cells were in use. The fire started in a cell with wood pellets and eventually spread to other cells, finally being declared extinguished nine months later on 24 August 1999. Clearing up took a further six months and the building was demolished in April 2000.

The normal procedures used for extinguishing silo fires proved inadequate in this incident and a number of other technical problems emerged. These included

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unexpected explosions, fire spread from cell to cell, compacting of silo contents, difficulties with emptying cells and breakdown of ancillary services.

These and other problems and the methods used in attempting to tackle them are described in this case study.

6.1.2 Background

6.1.2.1 Siting of the Silo

Esbjerg is Denmark's fifth largest city with 83 000 inhabitants. It is a regional center, with local airport and harbor serving the Danish offshore industry. The harbor is also a road and rail freight and ferry terminal. The silo was placed in the harbor area by the waterfront and was originally used for grain. Changes in shipping patterns caused a change of use and in 1990 a wood pellet factory was built next to the silo building.

6.1.2.2 Fire and Rescue Services in Esbjerg

Esbjerg council has responsibility for providing a fire service in Esbjerg county and supplies the leadership for the fire service. The fire fighting is contracted out to the private fire and rescue company, Falck, with council employees assisting on a part-time basis. Falck also provides ambulance and rescue services in the county area.

6.1.2.3 The Silo Building

The 85 m high building is from 1974 and has a capacity of 65 000 tons of bulk material in 23 cells.

6.1.2.4 Construction

The building was a traditional silo building for corn and similar products, constructed of reinforced concrete. The total height of the building was 85 m; 6 m as basement and 71 m high silo cells with an 8 m high loft over the silo cells. The footprint was about 1000 m^2 and the building comprised 23 cells, each with a capacity of 2300 m^3.

The silo walls were about 24 cm thick and were reinforced with 18 mm steel bar for every 15 cm horizontally to the outside and every 18 cm to the inside. The horizontal reinforcement was 12 mm steel bar for every 20 cm of horizontal concrete.

6.1.2.5 Emptying and Filling

The procedures for emptying and filling the silo cells were conventional.

Horizontal transport was by steel-sheet-enclosed chain conveyors with lateral slats, while cup elevators were used for vertical transport.

The bottom of each cell was funnel shaped to facilitate emptying by gravity through a gate valve onto a chain conveyor in the basement.

A further transport system was used in the silo loft, all transport being controlled from a central control room. Transport capacity for filling was 3–350 tons per hour.

6.1.2.6 Instrumentation

Each cell was fitted with four vertical wires, about 3 m apart. Ten thermocouples on each wire could be used for early detection of self-heating, which could be controlled by transfer to another silo or to initiate emergency emptying.

Temperature control was twice a week for filled cells and daily for cells being filled. Although stable and robust, not all the thermocouples were working.

Each cell was fitted with a surface measuring device to register degree of filling.

6.1.2.7 Explosion Venting

The top of each cell was fitted with 10 m^2 explosion venting, comprising five concrete panels. The silo loft was also constructed with a relatively lightweight framework, partly fire-proofed steel with 30 min fire resistance and partly timber frame with woodwool concrete panels. Fire ventilation hatches were provided but not all could be opened during the fire.

6.1.2.8 Description of Contents

The layout of the cells and their contents is shown below. Seventeen of the cells were full when the fire started in cell 6. Fire spread was initially to cell 8 and then to cell 9. All three cells were filled with wood pellets (Figure 6.1).

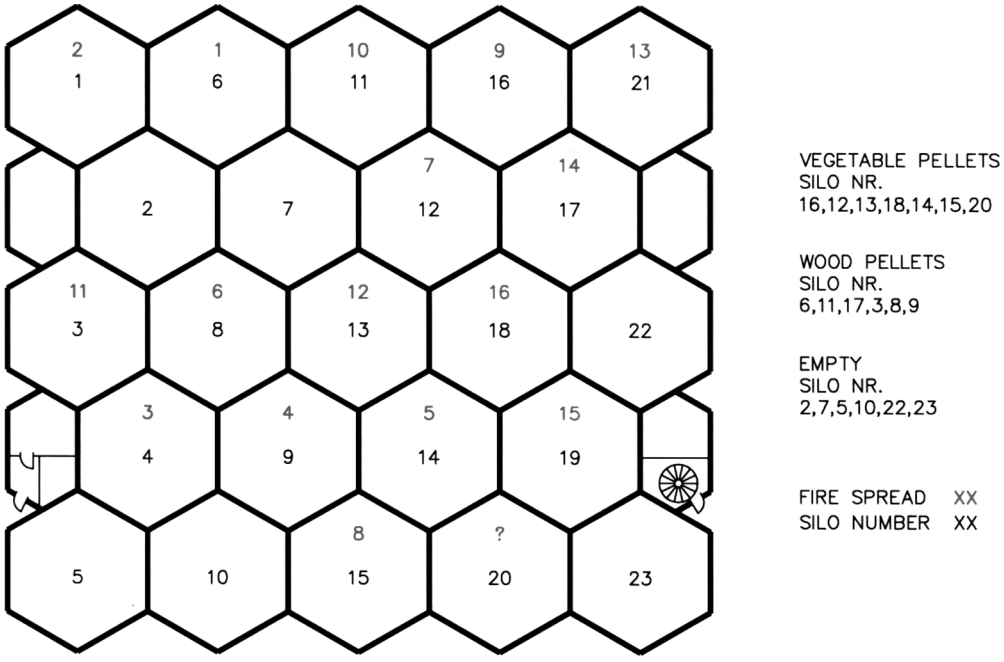

Figure 6.1 Top view of the silo plant in Esbjerg, Denmark; the course of the fire is indicated by the red numbers.

6.1.2.9 Wood Pellets

Wood pellets for use in domestic heating systems and local district heating and power stations are a relatively new renewable fuel source. They are mostly manufactured from wood waste, sawdust and chips which are pressed into pellets, about 1–3 cm long with diameter 1 cm. They normally flow readily, are stored in bulk stores and silos and transported in lorries with pneumatic delivery systems or as bulk cargo in ships.

6.1.3 Normal Extinguishing Practice

Silo fires often include the potential for explosions, as dust explosions or as ignition of products of combustion, with consequences such as injury to fire fighters, violent spread of fire or considerable property damage to the silo.

The tactics used in Denmark and shown below are based on experience with silo fires in grain and animal foodstuff production or in waste products from the woodworking industry.

6.1.3.1 Fires in Grain and Animal Food Silos

These silos are typically of concrete and containing several cells. Fires occur either from sparks or glowing embers carried through the normal transport system into the top of the silo or self-heating of the contents, leading to self-ignition inside the stored mass. Self-ignition can occur at several places in the bulk of the product.

Dust concentrations inside the silo during filling or near the silo during emptying are high enough to produce dust explosions. Fires in the bulk can thus be ignition sources for a dust explosion.

The initial attack is thus removing the possibility of dust explosion by applying medium expansion foam into the top of the silo cell, in the form of a 0.5–1 m thick layer and coupled with emptying the cell by normal emptying procedures from the bottom of the silo. If normal emptying cannot be carried out, a hole about $50 \times 50\,cm^2$ is cut in the cell, at the bottom of the vertical side, just above the cone. Fire hoses with spray nozzles are used here and the foam layer is maintained during emptying. Final extinguishment, using only water spray and not water jet, is performed outside the silo. Use of jets can cause dust to be thrown up into the air, especially inside the silo, which can give rise to dust explosions.

Water is not used directly in the cell, since absorption by some stored products can cause expansion which cracks the cell walls. Other products do not absorb water and hydraulic pressure from standing water in the bottom of the silo cell can also cause cracking.

Fires in concrete silo cells do not directly affect neighboring cells.

6.1.3.2 Fires in Wood-Containing Silos

Sawdust, wood chips and dust are the normal waste products from woodworking industries. These products are transported by pneumatic extraction systems to a

central silo storage, using cyclones and filters as separators. Silo contents can be emptied into vehicles or used as on-site fuel for heating.

Ignition by sparks from woodworking machinery can occur at the top of the silo, or at the bottom, caused, for example, by blow-back from a boiler using the wood as fuel. Fire spreads throughout the mass of the contents, often occurring as hot spots or isolated burning pockets.

Also here, there is often sufficient dust above the silo under normal working conditions that a fire in the bulk of the material can ignite a dust explosion.

Again, the initial attack is made by removing the possibility of dust explosion, either by applying medium expansion foam into the top of the silo cell or by using a water spray to bind and remove dust from the atmosphere at the top of the silo cell. Alternatively, the whole volume can be filled with high expansion foam, if this is available.

Full extinguishment is almost impossible, and procedures almost always include careful emptying of the cell contents through a bottom opening, with final extinguishment taking place outside the silo.

6.1.4 Incident Chronology

The following incident chronology is an extract from a fuller chronology (available only in Danish) which is based on various sources, including police and fire brigade incident reports.

It is limited to the first 32 days, when the fire brigade was in constant attendance. Fire brigade and other activities after this period and up to demolition of the silo building are summarized.

The chronology only covers technical problems associated with fire and fire fighting. It does not describe in detail other problems concerned with security (access limitation), personnel (availability for long-term deployment), information (press contact), or environment (disposal of several thousand tons of partly burnt material).

6.1.4.1 Day 1 – Initial Confusion

On 5 November 1998, 0657, the operator of the silo building requested technical assistance from the local rescue company, Falck. There was an unpleasant smell in the area and they suspected a fire in a silo cell.

Abnormally high concentrations of flammable gases are measured inside the building and windows broken to increase ventilation.

At 1320, a local journalist asks the police why 20 members of the rescue company are in hospital for poisoning.

At 1445, the police ascertain that there are no rescue services at the harbor but that a security company has established road blocks in the harbor area. The source of the poisonous release is not found but there are thousands of dead mice in the bottom of the silo building. A further 20 people working in the area are taken to hospital. Further road blocks are established.

At 1550, the police are informed that carbon monoxide is found to be present, but the hospital says there could be leakage of other material, since carbon monoxide is odorless.

At 1815, gas measurements taken inside the silo show high concentrations of carbon monoxide, sufficient to require use of breathing apparatus. The decision to empty the silo is taken, under the supervision of and with assistance from the fire brigade.

6.1.4.2 **Day 2 – Initial Problems**

Emptying of the silo proceeds slowly through bottom openings; the wood pellets are hot and compacted and are releasing flammable vapors. During the day, pellets at the top of the silo compacted to produce a 1–2 m thick layer. This is broken up by using water jets.

6.1.4.3 **Day 3 (Saturday) – Further Problems**

Emptying by suction carries on, with material being deposited on the quay, where it is extinguished by the fire brigade. Some extinguished material is sucked up into suction tankers. An explosion occurred in one of these, with minor injuries to the operator.

It is decided to make a hole of about 1 m^2 in the side of the silo cell, using explosives, in order to facilitate emptying. The top of the cell is filled with foam.

An initial explosion is a partial failure, only half of the explosives are set off. Just after midnight, the remaining explosives are detonated.

6.1.4.4 **Day 4 – Further Precautions**

Charges are placed for a further planned explosion to make a second hole on the other side of the silo while fire personnel observe the first hole (Figure 6.2).

The explosion is cancelled at 1000, since smoke is seen issuing from the first opening and ignition of smoke and gases, with subsequent explosion in the silo, is feared. More foam is added to the silo top.

Figure 6.2 Smoke emerging from an opening busted into the silo wall to facilitate emptying.

Figure 6.3 Steel reinforcements remaining after using explosives to produce an additional opening for emptying the burning silo cell.

The wood pellets are baked together and the steel reinforcing bars in the concrete silo walls prevent easy access and material flow (Figure 6.3).

The pellets are unwilling to run out on their own, even when prodded into action. After the Home Guard have supplied 75 detonators, the controlled explosion is planned for 2000 (Figure 6.4).

6.1.4.5 **Day 5 – Further Problems**

Just after midnight, more smoke starts to emerge from the hole that had been made followed by a rush of soot, ash and pellets. An explosion inside the silo ejects burning material from the opening in the side, giving rise to a flame estimated at about 150 m

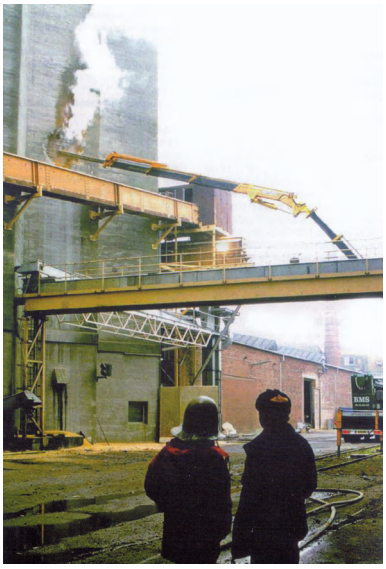

Figure 6.4 An attempt to increase the size of the hole in the silo side wall.

Figure 6.5 Explosive flame released from the silo after an internal explosion injuring two firemen and destroying a ladder truck.

high. Two firemen working on a ladder truck just 3–4 m from the hole manage to jump onto a neighboring roof and escape with slight burns. The ladder truck, which can be seen with extended ladder in the middle of the picture at the bottom, with headlights on, is a write-off (Figure 6.5).

Dust filters in the silo roof are ignited.

Assistance from other neighboring fire brigades and the Danish Emergency Management Agency (DEMA) regional center is requested to deal with the fire on the roof. DEMA personnel remain for the next four weeks. The harbor, an international ferry terminal, is closed to shipping and traffic. DIFT is contacted for technical assistance, with samples of wood pellets being flown to the laboratory.

Cooling of the silo using six water jets commences. Planning for accommodation for the extra personnel commences. Dumpers and lorries for collecting and removing burnt material are ordered but are not initially used as a further explosion is feared.

DIFT is contacted with regard to experience with silo fires.

Thermal measurements carried out by army personnel show that the fire inside the silo has risen by 6 m in 8 h. Some material is released from the silo opening (Figure 6.6).

6.1.4.6 **Day 6**

Two Liquified Pressurized Gas (LPG) tank ships are expected to arrive in two days but the local company is already running short as railway tank cars cannot get past the silo.

Smoke starts to develop in the basement below the silo.

Figure 6.6 Applying outside cooling to the wood pellets emptied from the silo.

Emptying of a neighboring cell number 7, containing grass pellets, into lorries is started. The contents show no signs of heating.

6.1.4.7 **Day 7**

No further heating in silo 6, temperatures in silo 1 are falling. Removal of ejected material from silo 6 and damaged vehicles commences.

6.1.4.8 **Day 8**

Silo 7 is emptied after 29 h. Emptying of silo 2 with wood pellets commences. Permission to recommence train services in the area is refused.

Temperature measurements indicate that 5 tons of oats on top of the silos has ignited.

DIFT is contacted as regards extinguishing of silo fires and solutions are suggested.

6.1.4.9 **Day 9**

Extinguishing using dry ice (solid carbon dioxide) and high-pressure water jets is discussed.

The temperatures in the basement of cells 1, 2 and 6 are 18–34 °C.

Equipment for adding dry ice to the top of silo 6 is set up.

6.1.4.10 **Day 10**

Addition of dry ice to the top of silo 6 commences. After 5 h, 2 tons is added. Addition through the hole in the side of the silo is attempted but the gas just runs out into the basement.

The temperature at the top of silo 6 is 15–20 °C and there is no carbon monoxide measured. A hot spot in the middle of the top half of the silo is found.

On the basis of these positive results, a resumption of a more normal situation is planned. This includes removal of barriers, resiting the command post, allowing normal ship and rail traffic and resumption of normal work in the rest of the silo building.

6.1.4.11 **Day 11**

At 0840, temperature under silo cell 6 measured at 25–45 °C, carbon monoxide level of 11%. 1000 kg dry ice added to silo top. Fire in oats on silo top extinguished. 1145, temperature in basement 70 °C, cell 6 still burning. 1900, temperature in basement 120 °C, no carbon monoxide. 600–800 kg dry ice added to silo cell 6 through holes in side. 2200, smoke in basement, 2345, sparks in basement extinguished.

6.1.4.12 **Day 12**

0015 Temperature rises from 120 to 260 °C, although there is possibly a fault in the measuring instrument. Odd sparks at 0600, no sparks or smoke at 0815. Measurements of concentrations of various gases including hydrogen sulfide in cells 1, 4, 6, 11, 17 and 23.

It is decided to let the carbon dioxide work for two days. 1000 kg added at 1800.

6.1.4.13 **Day 13**

0020 Temperature of 75 °C on concrete in basement. 1300, temperature of 320 °C in bottom of silo, hatches opened, black ash pours out, which is extinguished.

Various smells in different areas of the silo building. 2000 kg dry ice added to top of silo and 600 kg through holes.

6.1.4.14 **Day 14**

0020 Temperatures of steel under silo 6 now up to 300 °C, 7% carbon monoxide in silo.

6.1.4.15 **Day 15**

0200 Temperatures of steel under silo 6 now around 150–200 °C. 0230, 2000 kg dry ice added to top of silo cell 6 and 600 kg added through side holes.

0700 Emptying of cell 6 commences, using water jets to wash wood mass out through the side holes. After 1.5 h, material begins to flow out.

1655 Ignition of gases inside the silo from the burning material, 20 m high flames. Several explosions inside cell 6 (Figure 6.7).

1730 There is a fire in the material on the quay and in the roof construction over the silo.

Radio and telephone masts and aircraft warning lights on silo top inoperable. Thermographic measuring instruments recalled, tops of cells 1 and 11 are hot.

2100 Still too hot on silo roof for access by fire personnel, fear of falling machinery.

2130 Fire on roof dies out.

2230 Basement emptied of water.

6.1.4.16 **Day 16**

0335 Inspection shows silo roof construction burnt away, still burning in one corner.

0600 Sparks from vertical transport elevators, temperatures in basement up to 500 °C.

0800 Emptying of cell 6 restarted. No evidence of fires in other cells.

2230 Fire in slat transporter under silo 6 in basement, extinguished.

Figure 6.7 Flames emerging from silo top after an explosion of pyrolysis gases inside the silo plant.

6.1.4.17 **Day 17**

0800 Emptying of cell 6 halted, holes blocked by concrete chunks. Repair of mechanical transporter in basement commences, work carried out with fire personnel present and with constant gas measurements (carbon monoxide).

1400 Extinguishing with vinegar attempted, 40 L sprayed in bottom of cell 6.

1530 Cell 6 burning again.

6.1.4.18 **Day 18**

0500 Emptying of cell 6 recommences. Concrete blocks slat transporter, motor burns out. Band transporter set up.

1600 Silo cell 6 is now emptied from the bottom up to the holes in the side, except for concrete chunks. A mobile crane to help clear the roof is ordered, first available in three days. The top of cell 11 has cooled but cell 3 is just as hot as cell 6. It is decided to empty cell 3 directly into lorries and, if not burning, then into a nearby bulk store.

6.1.4.19 **Day 19**

1300 Fire in top of cell 9 with heavy smoke.

1900 2000 kg dry ice added to top of cell 9. No flames, just smoke observed.

6.1.4.20 **Day 20**

0800 Hot spots in cells 3 and 11. The mobile crane is broken down and a new one ordered.

1100 Wood pellets from cell 3 seem to be in order. Cell 17 begins to smoke.

1200 2000 kg dry ice added to cell 9, after the bottom is sealed with silicone sealant.

1500 Gas measurements on the roof by cell 6 show oxygen concentration of 3.6%, carbon monoxide over 1000 ppm, hydrogen sulfide over 500 ppm and carbon dioxide of 25 000 ppm, toxic levels for all gases.

1635 2000 kg dry ice added to cell 9.
1900 1000 kg dry ice added to cell 9. Air temperature of 38 °C in the cell.
2155 Mobile crane arrives.
2300 1500 kg dry ice added to cell 9. O_2 concentration 4%, temperature 50 °C.

6.1.4.21 **Day 21**

0900 Smoke from cells 8 and 17, gases from cell 11. Crane starts to remove roof construction. Access for workers to roof by staircase. All personnel on roof to wear breathing apparatus when dry ice is being added.
1500 2000 kg dry ice added to cell 9. O_2 concentration in cell 21%, CO 871 ppm, CO_2 11%, temperature 60 °C, increasing smoke.

6.1.4.22 **Day 22**

0200 CO concentration 200 ppm on roof, workers stay downstairs after break.
0250 150 kg dry ice added to cell 9.
0700 Ventilator erected on roof. Removal of debris continues.
1030 Foam from 150 L foam concentrate added to cell 9.
1130 Foam from 50 L foam concentrate added to cell 9.
1600 Foam added to cell 9.
1700 Gales stop work with crane.
1930 Foam added to cells 8 and 9.
2300 Foam added to cells 8, 9, 12 and 14.

6.1.4.23 **Day 23**

0200 Foam replenished in cells 8 and 9.
0430 300 kg dry ice added to each of cells 8 and 9.
0530 Crane restarts.
0900 Building owners and insurers suggest extinguishing with nitrogen and water spray, together with emptying by suction from silo top.
1400 DIFT recommends still using CO_2. Flooding with water at top of silo proposed. Foam added to cells 8 and 9.
1715 Concentration of explosive gases in cell 6 13%.
2000 Cells 20 and 23 are not affected and can be emptied.

6.1.4.24 **Day 24**

0000 Foam replenished in cells 8 and 9.
0015 Electricity supply fails.
0300 Smoke and heat from cell 12. Foam added.
1000 Six ventilators set up on roof, clearance work continues.
1130 3 tons foam concentrate ordered.
1345 Foam replenished in cells 8 and 9.
1930 Ventilators started, after electricity supply reconnected.

6.1.4.25 **Day 25**

0230 Fire in tar on roof extinguished with water.
1040 Foam replenished in cells 8, 9, 11 and 12.

1400 Foam added to all smoking cells. This removes smoke and CO from working area on roof.

2130 Workers on roof complain about excess smoke and foam.

6.1.4.26 **Day 26**

0400 Electricity supply to ventilators reconnected a second time.

0900 Two-thirds of roof now cleared. Foam is being added every 4–5 h. Emptying by suction to be attempted but for safety reasons without personnel on the roof. Video surveillance of roof area is set up.

1000 Strong fire developing in cell 16. Foam from 300 L concentrate added to cells 8 and 9.

1300 Electricity supply augmented. Foam addition to several cells all afternoon.

2200 Use of welding torch on roof necessitates laying down of foam on working area.

6.1.4.27 **Day 27**

0030 Foam added.

0100 Work stops due to fog. Restarts 0500.

Foam added to cells throughout the day.

Attempt to suck material out of cell 9 fails.

Increasing temperature in cell 3.

6.1.4.28 **Day 28**

Foam added to cells 8, 9 and 3 throughout the day.

0900 Cell 23 emptied, emptying of cells 10 and 17 commences. Elevator to silo roof re-established.

1500 Smoke from cell 21, foam added.

6.1.4.29 **Day 29**

0130 New attempt to suck from top of cell 9 fails.

0500 With added water jet, suction pipe has now broken through the crust at the top of the silo.

Foam added to various cells throughout the day.

6.1.4.30 **Day 30**

0900 Suction emptying of cell 9 stops, progress is too slow. Roof clearance is completed. Fire brigade reduced to four men for next two days and thereafter control twice daily. Police withdraw.

Over the next nine months, foam additions are made regularly to various cells, initially daily but, towards the end, more infrequently. Fires occur regularly during emptying operations, some extinguished by contractors using water jets. Cells are emptied but some contain smoldering or partly burnt material.

Several fires in piles of material emptied out onto the quay are extinguished (Figure 6.8). Attempts to sell off damaged material are unsuccessful; the wood pellets have a low fuel value and burn badly. Vegetable pellets and grain have begun

Figure 6.8 Wood pellets emptied from the burning silo cells and stored on the quay partly decomposed (black) and burned to ash (gray).

to decompose, ferment, sprout or go moldy and have to be sent to rubbish dumps. Foam-contaminated material cannot be sold as animal food. Concrete remnants have to be sieved from products. The mechanical handling system in the silo building, together with electricity supply, has to be repaired and re-established, so that normal emptying of silos to lorries or ships can resume. Presence of water and foam cause many short circuits in the re-established electricity system. Alternative handling systems cause problems with dust externally and are halted by the environmental authorities. Risk of dust explosions confirmed when a small explosion occurs inside a silo. Silos are cleaned inside using water jets and suction tankers.

After 287 days, the fire was officially declared extinguished.

After a further eight months, the building was demolished (Figure 6.9).

Figure 6.9 Demolition of the written-off silo plant after extinguishing the fire.

6.1.5 Problems Arising

6.1.5.1 Unexpected Explosions

The smoldering fires produced large quantities of non-burnt gases, as well as different pyrolysis products, many of which were flammable gases or liquids. Collected in the cells, explosions were a foreseeable consequence, if ignited.

6.1.5.2 Fire Spread from Cell to Cell

The initial cause of the fire was probably self-heating leading to self-ignition in wood pellets. The initial fire caused heating of the contents of neighboring cells, again giving rise to self-heating and ignition.

On day 13, further clouds of black smoke were observed from cell 6, probably caused by large quantities of wood pellets falling into the bottom of the cell. A gas explosion in the evening started a fire all the way up through the cell and a fire started in the silo loft. The uprush of smoke, flames and burning pellets could not be controlled and after 3 h the whole 900 m^2 silo loft was involved. In subsequent days, fire spread to the other cells, presumably by burning through the covers to the silo cells or possibly by self-heating. The following week's efforts were concentrated on controlling further fire development as well as emptying the different cells.

6.1.5.3 Compacting of Silo Contents

The silo contents were granulates, normally handled easily in bulk by using conveyors and transporters and flowing under gravity. Alternatively, they could also be pumped and sucked (vacuum transport) but these alternative transport systems which were tried did not have the same capacity as the in-place transport systems.

All the extinguishing methods tried had the effect of increasing water content locally. Direct water jets were used. Foam contains water, although at low levels. Even using solid carbon dioxide at –79 °C would cause local condensation. Local heat also caused water to be liberated from wood pellets, which condensed elsewhere. All these increases in water content would cause the granules to flow less easily and to clump together.

Further heat also caused granules to clump together and form areas and volumes which could be very large.

6.1.5.4 Difficulties with Emptying Cells

The cells were normally emptied by gravity flow to bottom openings. The effects of water and heat caused solid pockets, sometimes as internal bridges across the silo. These could only be broken up into smaller lumps by using mechanical force. Access to the mass of the contents was restricted to openings in the silo top, anything up to 80 m above the material in the silo.

Establishing emergency openings for emptying, one-third of the way up the silo walls, was attempted. The steel reinforcing bars in the concrete made efforts using explosives to provide extra discharge openings difficult; the concrete was shattered but a mesh of steel bars remained, restricting the hole size drastically.

Even though the lumps were loosely agglomerated, attempts to mechanically break them up only worked locally, anywhere beyond the reach of the mechanical implements being unaffected. Mechanical breaking up of lumps, which could be tens of cubic meters in size, was very laborious and time consuming.

6.1.5.5 Breakdown of Ancillary Services

The height of the building and limited access made work on the silo top difficult. Access to the silo roof and the tops of the silos is normally by a small four-person lift, with a spiral staircase for emergency use. Initially, all personnel had to use these routes for transport of equipment and materials.

After the fire in the roof, access was limited to the staircase, until the mobile crane arrived.

Electricity supply to the roof had to be re-established and supply to the rest of the building was severely affected by the quantities of water and foam used during fire fighting and suppression.

6.1.5.6 Measurements

Temperature measurements of silo surfaces were carried out from ground level using military personnel and equipment (Figure 6.10).

Measurements of gas concentrations – carbon monoxide, carbon dioxide, oxygen and flammable gases – were made regularly. The conventional instruments used were not sufficiently robust to enable satisfactory readings to be taken in the hot and damp environments in which measurements were usually made.

6.1.5.7 Weather

The Danish weather in November and December, with low temperatures, gales and fog, had its usual effects on operations (Figure 6.11).

Figure 6.10 Measurement of the outside surface temperatures of the silo cells.

Figure 6.11 Ice formation at the floor grating around the silo.

6.1.5.8 **Access Lofts**

The fire in the silo roof destroyed all handling equipment and halted all access to the silo cells. The debris from this had to be cleared away before extinguishing or emptying could be attempted (Figure 6.12).

All material had to cut away and lifted down by crane. Personnel access was by the single staircase. The clearance was performed round the clock, with less than eight daylight hours available. There was constant evolution of smoke, heat and flammable and poisonous gases and extensive use of water and foam by attendant fire fighters.

6.1.5.9 **Personnel**

Fire brigade incidents are usually of short duration, a matter of hours. A fire brigade is not usually prepared to be in constant action for the weeks of activity that were necessary with this incident. Even though supplementary personnel were readily

Figure 6.12 Demolished structures at the silo top hampering the extinguishing works.

available, the task of coordinating and finding board and lodging for them was a further drain on the local resources.

6.1.6
Costs and Material Usage

Insurance compensation comprised € 1.7 million for goods, € 1.4 million for buildings, € 2.4 million for machinery and equipment and € 2 million for clearing up expenses, including disposal of extinguishing water. Loss and damage to fire brigade equipment was € 0.5 million.

In the first two months, over 700 people were involved, using 16 000 man hours, of which 3500 were from fire and rescue personnel. The demolition alone involved 61 police personnel, for 225 h.

Twenty-eight people were injured during the course of the incident.

Consumption of materials was 4.5 tons of foam concentrate, more than 19 tons of dry ice, over 1 million tons of water and 80 kg of dynamite, used for demolishing the 20 000 ton silo.

Grateful thanks are due to Karsten Ive of the Development Unit of the Danish Emergency Management Agency, for permission to use much of the material presented in this case study and to Esbjerg Council Emergency Services for permission to use much of the photographic material.

6.2
Further Case Studies

Rolf K. Eckhoff

6.2.1
Smoldering Gas Explosion in a Large Storage Facility for Grain and Feedstuffs in Tomylovo in the Kuibyshev Region of USSR

This case history was reported by Eckhoff [1]. The large storage facility for grain and feedstuffs consisted of four sections of 60 silo cells each, that is, 240 silo cells altogether. Each cell was of $3 \times 3\ m^2$ square cross section and 30 m height. The first explosion occurred in December 1987 in a silo cell containing moist sunflower seed, which was not supposed to be stored in such silos due to the risk of self-heating. However, this had nevertheless been done, and the resulting self-heating developed into extensive smoldering decomposition during which methane and carbon monoxide were produced and mixed with the air in the empty top part of the silo, above the powder bed surface. It is reasonable to believe that the primary explosion was in this mixture of explosive gas and air, and that the ignition source was the smoldering combustion when it penetrated to the powder bed top surface. However, dust deposits on the internal silo walls and roof may well have become entrained by the initial blast and involved in the explosion.

Figure 6.13 The concrete silo complex in Tomylovo, Knibyshev, Russia, after having been damaged by several successive smoldering gas explosions in silo cells during 1988 and 1989. From Eckhoff [1].

This was only the first of a large series of 20–30 subsequent explosions that took place in the same facility, in one silo cell after the other, during 1988 and 1989. Figure 6.13 shows a photograph of the silo complex after several silo cell explosions.

There are two main reasons for this continued explosion activity in the silo complex. The most important is the heat transfer from a silo cell in which smoldering combustion is taking place to the neighboring cells. Such heat transfer was facilitated by the large contact surface area between the cells provided by the square cross section. Furthermore, the pre-fabricated construction elements used throughout the entire facility may have been comparatively poor heat insulators.

The second main reason for the repeated explosions was that sunflower seed was not the only material in the facility that was not supposed to be stored there. Some of the silo cells contained buckwheat and wheat grain of higher moisture contents than the maximum permissible limits for storage in such facilities.

During the period of repeated explosions a series of attempts were made at breaking the unfortunate chain of events. Cells were opened at the top for inspection. However, this admitted fresh air to the smoldering mass and enhanced the combustion process. Attempts were made at quenching and cooling the powder mass by liquid nitrogen, but this was only partially successful.

It was agreed that the use of water for extinguishing the smoldering combustion in the silo cells was not feasible. Limited quantities of water would probably enhance the self-heating process rather than quench it, whereas use of extensive quantities would increase the load on the silo walls and cause collapse of the structure.

At one stage it was discussed whether the whole facility could be blown up to put an end to the problem. However, this was considered too hazardous. The final solution chosen was to just leave the entire facility to itself and await a natural termination of the problem over time.

Besides obeying the rules specifying which materials can be stored in silos, systematic use of portable gas analyzers for early detection of hydrogen, methane and carbon monoxide in the silo cells was suggested as the best means for preventing similar accidents in the future.

6.2.2
Smoldering Gas Explosion and Subsequent Successful Extinction of Smoldering Combustion in Pelletized Wheat Bran in a Silo Cell at Nord Mills, Malmö, Sweden, in 1989

The course of events of this case history, reported by Eckhoff [1], was as follows:

Saturday 28 January, 0700: the night shift stopped the production for the weekend according to schedule, and all activity in the grain silo plant terminated.

Saturday 28 January, 1000: according to Nord Mills' safety procedures, the safety guard team made its inspection round through the entire plant. Nothing special was observed. No persons were encountered.

Saturday 28 January, 2300: a bang, muffled by the noise of strong winds, was heard in the neighborhood, but no action was taken.

Sunday 29 January, 0930: during its scheduled inspection round, the safety guard team discovered fragments of shattered window panes spread over the entire yard. Inspection of the roof of the silo building revealed that the roof of an intermediate star cell had blown up, as shown in Figure 6.14, and that dense smoke was emerging from the open cell top. The height of the cell involved was about 36 m and its cross-sectional area about 20 m^2. Most of the silo was empty, the pelletized wheat bran occupying only the seven first meters above the cell bottom.

Sunday 29 January, rest of day: fire brigade and other personnel were called, and the entire plant area was cordoned off. About 2000 kg of gaseous carbon dioxide was pumped into the burning silo from above through a long vertical pipe extending right down to the surface of the smoldering pellets. The situation is shown in Figure 6.14.

Monday 30 January, early morning: the discharge valve at the cell bottom was removed, and discharge of the pellet mass, using a mobile suction unit, was started. This gave rise to increased smoke production, and at 0330 more carbon dioxide was loaded into the silo cell from above.

Tuesday 31 January: the discharge operation was interrupted. Carbon dioxide was emerging through the bottom silo exit, and more was loaded into the silo at the top.

Wednesday 1 February: more carbon dioxide was loaded into the silo at the top. From 0300 to 1250 the smoke development was enhanced by vibrations due to operation of

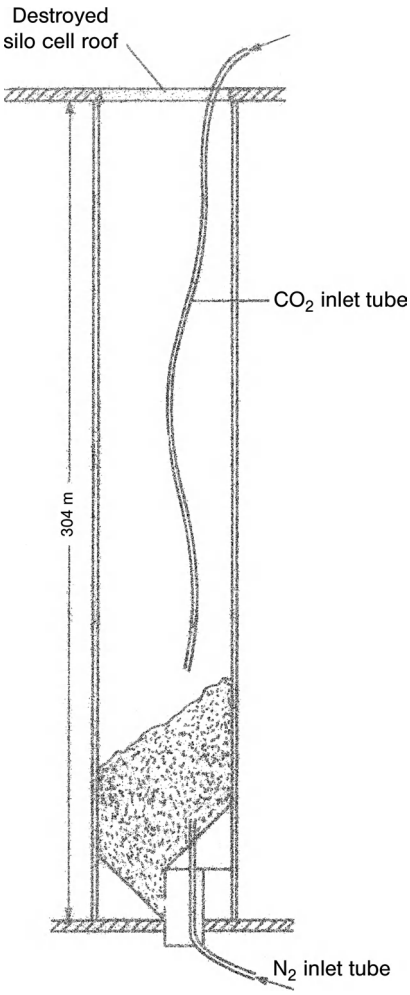

Figure 6.14 Cross section of silo in Malmö, Sweden, in which a destructive explosion of a smoldering gas–air mixture took place in 1989. The arrangements for subsequent supply of carbon dioxide and injection of nitrogen are indicated. From Eckhoff [1].

another silo cell. The smoke temperature just above the pellets was 96 °C, and just above the silo top 45 °C.

Thursday 2 February–Wednesday 8 February: smoke development and temperature rise were suppressed temporarily by loading several tons of carbon dioxide into the silo from the top, but there was only slow permanent progress. Temperature rise was observed in the material stored in the four larger adjacent silo cells.

Thursday 9 February–Saturday 11 February: holes were drilled through the silo bottom and at intervals a total of several tons of nitrogen were pumped into the pellets from below, while carbon dioxide was charged from above.

Monday 13 February–Wednesday 15 February: some 6000 kg of carbon dioxide and 3000 kg of N_2 were injected into the burning pellets. Temperatures in the burning and adjoining cells and contents of oxygen, CO and CO_2 in the gas above the pellets were monitored regularly.

Monday 20 February: the smoldering combustion in the wheat bran pellets had finally been brought to an end.

This case history illustrates that fighting smoldering combustion in large silo complexes is not only a matter of quenching or terminating the oxidation reaction, but also indeed a matter of cooling massive bulks of poor heat conductors to a temperature level at which the combustion process will not start again once air is re-admitted to the system.

6.2.3
Extinction Using Water of Smoldering Fire in a Fish Meal Silo in Norway in 1992

This case history was reported by Eckhoff [2]. During the struggle to fight the smoldering fires in the silo complex in Tomylovo, Russia (see above) it was agreed that the use of water was not feasible. The arguments were that limited quantities of water would probably enhance the self-heating process rather than quench it, and use of extensive quantities would increase the load on the silo walls (hydrostatic pressure) and cause collapse of the entire structure.

In view of this it is interesting to consider the use of water for extinguishing a fire in a fish meal storage silo in Norway a few years later. In this case the silo was cylindrical, of height 20 m and diameter 4.5 m. The bottom hopper was wedge-shaped and fitted with a horizontal screw conveyor for discharging of the meal. The sides of the hopper were at 60 degrees against the horizontal plane.

The entire sequence of events was as follows:

The fresh fish meal from the production plant was filled into a mixing silo for being recycled and conditioned, before being transferred to a storage silo.

In order to prevent self-heating in the meal during the conditioning period, recycling by discharging the meal from the silo bottom via the screw conveyor, and returning it to the silo at the top, was started.

After some days it was discovered that the meal discharge operated by funnel flow rather than by mass flow, that is, most of the material was not taking part in the recycling process.

It was realized that digging out the material in the "dead" zones in the silo would be necessary, but, due to lack of time, this work was not started until four weeks later. This made it possible for self-heating to develop in the stored fish meal.

When trying to discharge the meal from the silo bottom after the four-week break, bridging of the meal across the entire silo cross section was discovered.

Digging out was started from the silo top. When material had been removed down to the level of 2 m above the transition between the cylindrical silo wall and the hopper, the digging had to be stopped. The three main reasons were smoke development, that the meal was too hot to stand on and handle and that the meal had become very hard (a steel spear could only be forced about 10 cm into the meal by hand).

A nitrogen atmosphere was established in the silo above the meal surface.

The fire brigade was called. However, they did not know how to deal with the matter, and left.

The nitrogen atmosphere in the silo was kept for three weeks, but the smoldering fire inside the meal did not extinguish.

It was then decided to try to fill water into the silo. But first information was collected about the strength of the bottom/hopper part of the silo. It was concluded that the bottom part could just about take the hydrostatic pressure that might result from soaking the meal with water.

Water was filled into the silo. "Cracking" sounds were heard from the hopper section.

After 10 days the silo bottom was opened, and the water was drained out.

Workers were admitted into the silo again to resume the digging-out work. The meal was then just like concrete and had to be removed by using pickaxes and hammers and chisels.

After some digging out regions with smoldering meal were once more encountered, and the digging had to be interrupted.

The silo was once more sealed, and the remaining fish meal soaked with water.

After 10 more days the water was drained out, and the digging out resumed. This time it was possible to empty the silo completely.

Outwards buckling of the hopper walls was observed.

The total time, from the onset of the efforts to extinguish the fire to final completion, was about two months. This story illustrates that it still remains to develop adequate procedures for extinction of fires in silos.

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7
Fighting Silo Fires

Ulrich Hoischen, Jörg Kayser, and translated by Ulrich Krause

7.1
Introduction

From the statistics "Dust explosion events" [1] of the German Berufsgenossenschaftliches Institut für Arbeitssicherheit (BGIA) one can see that silos and bunkers are among those installations where dust explosions occur comparatively frequently. The statistics in Figure 7.1 shows the portions different installations hold on the dust explosion events.

Fires and explosions may occur during storage of combustible materials in silos. These products can be found, for example, in the woodworking industry (wood dust and chips), the food industry (flour, milk powder, malt and others), in agriculture (storage of grain and animal feed), in the production of plastics (polyethylene and polypropylene powder or granules) and during metal production (aluminum or magnesium dust or snatches).

Whether an incident started as an explosion and later turned into a fire or the other way around mostly can be revealed unambiguously during investigation. According to those reports, sometimes inappropriate measures of fire fighting promote the propagation of the fire or even an explosion. The consequences are sometimes disastrous, especially because of the presence of individuals (fire fighters). Sometimes injuries or even fatalities have to be noted.

In the newspapers reports like the following can be found:

"Casualties in a silo fire – during a smoldering fire in a multistorey grain silo two fire fighters lost their lives. When extinguishing the fire a dust explosion occurred causing the ceiling to break down. Five fire fighters were buried under the debris. The rescue service could only save three of the entombed ones. The salvage works still continue." Figures 7.2 and 7.3 give some impressions of this event.

During another incident the fire service decided to let a silo filled with wood chips burn down intentionally in a controlled way. The attempt to cut a hole into the silo roof ended in an explosion. Fortunately, only two of the fire fighters were slightly injured.

A third example highlights the hazards connected with wrong tactics during fire fighting. During extinguishing a fire of wood chips in a silo plant, a dust explosion

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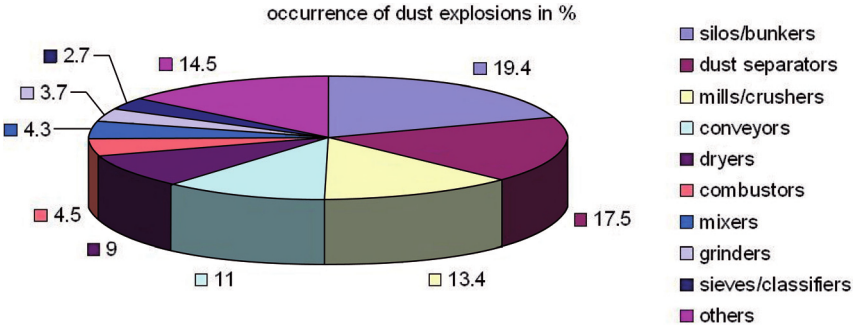

Figure 7.1 Percentages of dust explosion events attributed to different groups of installations.

occurred. After a short evaluation of the situation the professional fire department received the order to open the lower revision door of the silo to attempt extinguishing the fire directly with a syringe. The stored material was dispersed in this way and the subsequent dust explosion led to considerable losses in the entire silo system.

In the following an example is given, in which self-ignition in a foodstuff silo generated a fire to demonstrate the problem of fire fighting in a silo. After a number of unsuccessful trials with different extinguishers, inertization with nitrogen was conducted, which finally ended in a success.

In another example demonstrating the test inertization of a malt silo the fundamentals of an inertization with gas intrusion from the silo top and from the silo bottom through the discharge opening are described. The test inertization was undertaken to check the function and the dimensioning of improvements of fire and

Figure 7.2 Extinguishing works during a grain silo fire.

Figure 7.3 Nitrogen storage tank for explosion suppression during extinguishing a silo fire.

explosion protection measures in connection with regulations according to the German Federal Immission Protection Act.

Finally, a third example shows the application of the extinction agent gel Firesorb® in connection with the intrusion of nitrogen. In this case a final success of the extinction could not be achieved by inerting.

It has to be stated that especially the fighting of silo fires in certain circumstances may be very time consuming and if wrong extinction tactics are applied a high potential of danger may rise. Additionally, fire fighting may be complicated due to hampered access to the fire site or to the silo plant itself.

7.2
Inert Gases for Silo Fire Fighting

On silo fire fighting inert gases are injected into the volume to be protected targeting to reduce the concentration of oxygen to such a level that a fire is extinguished finally. For doing this, the volume fraction of oxygen around the "hot spot" has to be reduced below 2% until cooling of the hot spot is observed.

If the hazard of a dust or gas explosion cannot be excluded, the void volume in the silo has to be filled with inert gas such that the limiting oxygen concentration (LOL) for explosion initiation is under-run. The limiting oxygen concentration of a dust/oxygen/inert gas mixture or a flammable gas/oxygen/inert gas mixture, respectively, is the highest volume fraction of oxygen in such a mixture which does not allow ignition.

Reducing the oxygen concentration in the void volume at the silo top eliminates the hazard of an explosion. The LOL is a material characteristic and ranges from 5% (aluminum and magnesium alloys) to 10% (cornstarch, wood dust and polyethylene). For lignite or black coal dust the LOL is even higher, between 12 and 14%, respectively.

In principle every non-flammable gas can be used for inerting. The inert gases used mostly are

- nitrogen,
- carbon dioxide,
- cooled flue gases,
- water vapor,
- gas mixtures like Inergen®,
- noble gases.

In practical applications especially nitrogen and carbon dioxide are preferred. Noble gases and gas mixtures are in most cases too expensive with respect to a long-term inerting process. Water vapor leads to a mostly undesired wetting of the product due to condensation. Moreover, the inerting effect vanishes when the water condenses.

The production of flue gases for inerting, as frequently applied in the Eastern European mining industry, does not seem to be suitable for fighting silo fires due to undesired side effects.

7.3 Nitrogen

With a density ratio of 0.97 to air, nitrogen is only negligibly lighter than air. Physiologically nitrogen is not hazardous and can be used for inerting without problems.

Smaller amounts can be stored in bottle bundles, larger amounts in low-pressure vessels. Alternatively, nitrogen can be produced on site. For doing so, so-called pressure swing adsorption or membrane reactors are used which extract nitrogen from ambient air by reducing the number of oxygen molecules at molecular sieves.

Using nitrogen the adjacent rooms have to be carefully locked. Before entering these rooms it has to be checked if the level of oxygen is sufficient for breathing.

7.4 Carbon dioxide

Carbon dioxide has a density ratio to air of 1.53 and is thus significantly heavier than air. Physiologically it is problematic due to its effect on the respiratory center. Besides the replacement of oxygen the prescribed limits of maximum workplace concentration and deployment tolerance limits for the rescue services have to be considered. The hazard of thermal decomposition mentioned sometimes is usually not relevant because it takes place at temperatures much higher than 1000 °C.

Smoldering fires of organic materials have temperatures well below this. Only for fires in metal powders has the hazard of decomposition of carbon dioxide to be considered.

Storage of carbon dioxide usually is done in bottle bundles for small quantities and in low-pressure tanks for larger quantities. In most cases carbon dioxide is delivered

to the fire site in low-pressure tanks after a fire has been noticed, evaporated on site and then injected into the silo via a control path.

As with nitrogen, the adjacent rooms have to be locked. With carbon dioxide, rooms on the deeper floors, like cellars and so on, have to be locked, too. In these rooms carbon dioxide can accumulate. Before re-entering these rooms oxygen and carbon dioxide concentrations have to be measured.

If – after successful fire fighting – the silo has to be flushed with fresh air, the exhaust gas has to be directed in such a way that accumulations of carbon dioxide are avoided.

7.5
Fighting a Silo Fire in an Animal Food Production Plant

7.5.1
Description of the Situation

An agricultural company operates a food production plant with different silos and mixing equipment. It consists of a building complex with two silo levels and an integrated machine hall.

In the upper silo gallery there are silo cells filled with raw components. In the lower gallery, cells for intermediate storage of raw components and products exist. The cells have volumes from 17 to 580 m^3. In the machine hall the raw components and products are conditioned, mixed and filled into bags.

7.5.2
State Before the Fire

In a silo cell at the upper gallery a fire occurred. Eight weeks before the fire this silo cell (465 m^3) had been filled with 220 tons (about 460 m^3) of sunflower extraction groats. Due to the unusually warm weather at the day of filling, the material had been filled in having a temperature of 25 °C, while normally the filling temperature was about 15 °C.

About four weeks before the fire the material solidified such that during discharge a layer was formed above the first discharge funnel. The second section of the silo could be emptied with a bridge remaining above an interior saddle. Out of this bridge two to five tons of material broke down and were discharged on a daily basis.

In the following the excavation of the bridge from above and the discharge of the solidified material from the funnel were continued.

Making a "break-through" through the solidified material below the saddle, the workers did not notice the smell of a fire.

7.5.3
Outbreak of the Fire

After emptying of the silo had been interrupted for about one week, first signs of a fire were noticed. The outbreak of the fire was presumably due to self-ignition of the

sunflower extraction groats. The self-ignition was promoted by the high temperature during stocking in connection with convective flow.

7.5.4 Fire Fighting

First day:

At the day the fire was noticed for the first time, the personnel detected a mild evolution of smoke at the top of the silo at 6:30 a.m. After extracting a sample of material through a maintenance opening in the silo ceiling, the smoke evolution was enhanced. At about 9:00 a.m. the silo cell and the upper gallery were completely filled with smoke. At 10:00 a.m. the fire department was alerted and local fire volunteers marched to the site.

The following procedure was agreed upon:

- to position a foam blower on the 44.3 m gallery and to prepare for fire fighting with light foam,
- to prepare lances for the controlled injection of inert gas into the presumed hot spot,
- to contract a supplier of nitrogen,
- to install a fire watch.

The maintenance holes on top of the silo were deliberately left open to prevent the hazard of an explosion of accumulated smoldering gases.

At about 5:30 p.m. the smoke development intensified and the smoke became darker. The visibility was not more than 1 m. An inspection of the conditions in the silo was no longer possible. The fire volunteers were called again at 6:00 p.m. From 6:30 p.m. until 9:00 p.m. the silo cell was flooded with light foam. After this, smoke generation and temperature decreased.

Second and third days:

In the morning of the second day the development of smoke increased again. At 12:00 a.m. the fire fighters noticed flames in the upper section of the stored material together with decreasing smoke generation. The injection of CO_2 only led to a short slow down of the fire.

After the flames occurred again, the fire department was called once more. Applying water through lances allowed them to extinguish the flame, but enhanced the development of smoke.

From 2:00 p.m. to 6:00 p.m. the fire fighters installed a fire watch. During this time the temperature of the ceiling above the cell increased strongly. Controlling the situation within the silo cell became more and more difficult.

After open flames had been noticed again, the cell was flushed with light foam several times. Applying foam suppressed the evolution of smoke. During the night, however, smoke developed again. By injecting water the conditions in the silo could be stabilized with less smoke development than the day before.

Fourth day:

At the fourth day the Deutsche Montan Technologie GmbH (DMT)-Fachstelle für Brand- und Explosionsschutz (DMT Fire and Explosion Protection Unit) was included in the rescue team. With respect to possible hazards of dust explosions which in cases like this always have to be considered, it was decided to switch fire fighting completely to inerting with nitrogen from 12:00 a.m. on.

The following measures were taken:

- intrusion of nitrogen at rates of up to 200 m^3/h,
- sealing of the silo cell,
- temporary injection of light foam for cooling,
- measurement of temperature using an infrared technique and measurement of oxygen and carbon monoxide.

Measuring the volume fraction of oxygen, the success of inerting (reduction of the oxygen concentration to 2–4%) could be stated at 4:00 p.m. In addition, the concentration of carbon monoxide was monitored. This value indicates the development and intensity of the fire. The concentration of carbon monoxide increased during this time from more than 50 ppm to about 180 ppm.

Using an infrared sight three sections with glowing nests could be identified at the surface of the stored material.

Fifth and sixth days:

Because of the small cooling effect of nitrogen, at the fifth and sixth days an additional injection of light foam into the silo cell was performed to finally extinguish the glowing nests at the surface.

Maintaining the sealing of the silo cell, together with the injection of nitrogen, an oxygen concentration of about 5% could be perpetuated in the silo.

No actions except monitoring were undertaken at the seventh day.

Eighth and ninth days:

At the eighth and ninth days, with ongoing inertization the following inspections of the silo cell were undertaken:

- visual inspection of the surface of the stored material using an infrared-sight device,
- measuring the temperature and CO concentration in the sections covered by the fire,
- emptying the fire sections using a countersink.

As a result of these inspections, it could be stated that the fires were extinguished. The fire compartments initially noticed obviously were surface fires and not hollow fires as initially presumed.

7.5.5 Emptying the Silo Cell

Because of the successful extinction the silo cell could be emptied immediately. Since flaring up of the fire with influx of air could not be excluded and since it was not clear if the smaller hot spots had been noticed and extinguished entirely, the following measures were taken.

At first the discharge conveyor had to be put into operation under continued injection of nitrogen.

Loosening the contents of the silo with excavators and transporting the loose material away had to be undertaken from outside. The silo could not be entered. It was decided to continue inerting the silo to prevent dust explosions and also the hazard of material flaring up again.

Because the discharge conveyors had to be set into operation for emptying the silo and the maintenance holes had to be opened, it was not possible to keep the oxygen concentration at a level of 5%. A limit of 12% was fixed still allowing the prevention of a dust explosion.

Monitoring of the concentrations of carbon monoxide and oxygen remained necessary. Emptying the silo could be finished at day 22 of fire fighting.

7.5.6
Summary and Conclusion

Due to the good cooperation between the operating company, the fire fighters and the DMT the silo fire could be extinguished relatively quickly. The fire had only minor effects on the operation of other parts of the factory so that customer services could be continued.

For fire fighting the following figures hold:

- duration of fire fighting 22 days (including emptying),
- duration of inerting 15 days,
- nitrogen used: about 40 000 m^3,
- maximum nitrogen flux rate: 200 m^3/h,
- foam used: about 2000 m^3 light foam and 5 m^3 water.

7.6
Test Inertization of a Malt Silo

7.6.1
Description of Situation

The test inertization was performed to approve functioning and dimensioning of an inertization installation in the case of a fire. It was installed to improve fire and explosion protection measures according to German immission prevention rules.

The silo plant consisted of nine individual silo cells from 135 m^3 to 423 m^3 in volume and was protected by an inertization with carbon dioxide.

The installations were designed such that inerting could be carried out from the silo top in the case of a fire for reducing the hazard of an explosion. Fire fighting was intended to be undertaken via gas injection shafts at the silo discharge.

The test inerting served to check dimensioning and functionality of the inerting installation at a 423 m^3 silo. Additionally, valuable hints could be obtained with respect to the technical procedure and necessary operational measures.

7.6.2 Estimating the Necessary Amount of Inert Gas

On estimating the necessary amount of inert gas a distinction was made between inerting from the silo roof into the void volume in the upper part of the silo (prevention of dust explosions) and inerting from the silo bottom through the bulk material (extinction of the glow fire). The parameters of inertization were based on experience and selected as follows:

(a) Inerting from the silo top (explosion prevention)
- reduction of $O_2 \leq 10$ vol.%,
- intended time of inerting 2 h,
- specific inert gas ratio about 1 m^3 CO_2/m^3 void volume,
- necessary inerting rate about 200 m^3/h.

(b) Inerting via silo discharge (extinction of glow fires)
- reduction of $O_2 \leq 2$ vol.%,
- intended time for inerting 4 h,
- specific inert gas ratio about 1 m^3 CO_2/m^3 bulk volume,
- necessary inerting rate about 100 m^3/h.

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8
Necessary Fire Prevention Measures for Silos with Flammable Solid Bulk Materials in Connection with Inerting During a Fire

Ulrich Hoischen, Jörg Kayser, and translated by Ulrich Krause

8.1
Inerting of Silos with Flammable Solid Bulk Materials in Case of Fire

From statistics of incidents it is well known that silos filled with flammable bulk materials are among that equipment where the frequency of fires or eventually dust explosions was above average.

Since the early 1980s, especially, inerting has become more and more important as an option for fire extinguishing. Unfortunately, mistakes in fire fighting tactics have repeatedly resulted in dust explosions giving rise to casualties or severe injuries and economic losses (see also Chapter 7, "Fighting Silo Fires").

For this reason it seems recommendable that integrated concepts for fire prevention and fighting are applied to silos where flammable bulk materials are stored.

Additionally, for testing of functionality and dimensioning of the inerting system, at least one test run of silo inerting should be performed. This can be done for example during a fire fighting exercise which should be carried out regularly in cooperation with plant personnel with local fire fighters.

In the following, recommendations are given for construction, processing and operational measures when inerting of the silo is considered, especially when inerting is undertaken only in the case of a fire.

In such a case injecting inert gas is intended to extinguish the fire, eventually together with other extinguishing agents. In addition, by inerting the hazard of dust explosions during fire fighting and subsequent emptying of the silo should be reduced.

The following recommendations do not purport completeness or general validity. Possibly, depending on the fire or explosion hazard of the bulk material stored, even more restrictive requirements than those mentioned here may be necessary, while in other cases less restrictive ones may seem sufficient. For an appropriate assessment of the fire or explosion hazard, each silo plant has to be considered individually.

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8.2
Recommendations for Construction, Processing and Operation

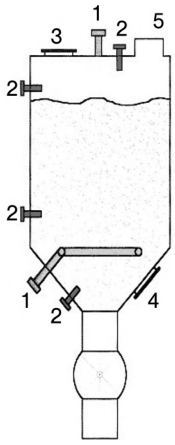
8.2.1
Construction

For inerting a silo where flammable bulk materials are stored, sockets for the injection of inert gases and openings to mount monitoring probes should exist. The same applies to emergency openings for silo emptying. In particular, the following should be considered:

- Several sockets for inert gas injection should be mounted to the discharge funnel and the top of the silo. These sockets should be mounted in such a way that the bulk material cannot block the gas injection. An example is shown in Figure 8.1.
- On the way from the inert gas container to the injection sockets gas pipes should be installed. These pipes should be marked as inert gas carriers for fire fighting.
- Leakages at the discharge openings and at the aspiration systems where during inerting air could entrain should be avoided.
- For monitoring the efficiency of inerting at least three 0.5 in. openings for gas concentration and temperature measurements should exist. These openings should be located at the discharge, at half the height of the silo and at the silo top.
- To avoid an uncontrolled escape of the inert gas the silo should be sealed properly. For openings which have to be kept open during normal operation easy-to-use closures should be right at hand.
- To guarantee a safe emptying of the silo during inerting or after fire fighting the silo should have emergency openings of sufficient size at locations easy to access.

A sample sketch for such an installation is given in Figure 8.2.

Figure 8.1 Example for injection of inert gas at a discharge funnel.



1 Inert gas inlet
2 Openings for measurement probes
3 Revision flaps
4 Opening for emergency emptying
5 Filling hole

Figure 8.2 Example for emergency opening at a discharge funnel.

8.2.2
Measures During Processing and for Fire Detection

During regular inspections signs of a fire like fire odor, release of smoke or water vapor or increase of temperature should be noted.

Automated detection systems reacting to smoke, carbon monoxide or temperature increase are able to detect a fire in this early stage of development; see Figure 8.3. This allows an early response. Examples for such systems are

- detectors for fire gases,
- active (suction) smoke detectors,
- infrared cameras,
- temperature probes.

The most appropriate detection system for a specific silo plant has to be identified in an individual hazard study.

8.2.3
Operational Measures

To perform an efficient and ultimate inerting of a silo in the case of a fire some additional facts have to be known. In cooperation with the deliverers of inert gas, management of the silo plant and silo fire experts the following items should be clarified to take quick and appropriate actions in the case of a fire:

- What is the bulk material to be inerted and which inert gas is the most suitable for it?
- What are the flammability/explosion limits and what is the maximum permissible oxygen concentration for the bulk material in question?
- Which dealer of inert gases is able to supply a sufficient amount of the inert gas as fast as possible?

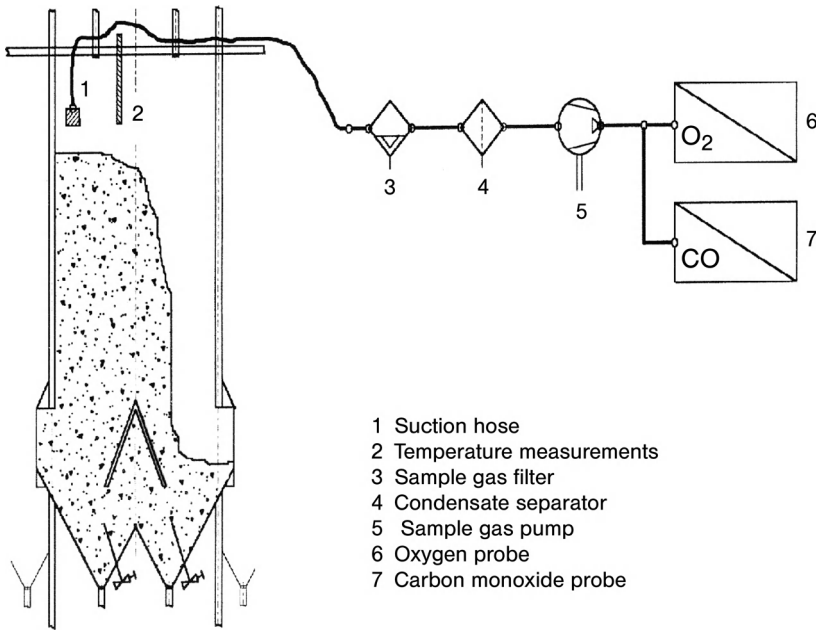


Figure 8.3 Example for an automated early fire detection system in a silo using carbon monoxide and oxygen monitoring.

- Are systems for oxygen and carbon monoxide monitoring and temperature measurement available?
- Does the gas supply system for the inert gas have the necessary premises for measurement, control and safety?
- Can the silo be sealed sufficiently?
- Is the silo equipped with appropriate supplies for inert gas injection?
- Which other supplies are necessary for the inerting equipment?
- What is the permissible overpressure in the silo and does the supplier of inert gas have the safety equipment to prevent overpressures?

The operational measures for silo fire fighting with inert gases should be summarized in an "alarm plan for inerting in the case of a fire." This plan should include the following information:

- a list of all persons or units to be informed, for example plant manager, local fire department, authorities, insurances and external experts,
- a list of dealers of inert gases which are able to supply instantly inert gas, either in bundles or in liquid gas containers with evaporator,
- a list of companies or institutes which can instantly provide measurement equipment for oxygen, carbon monoxide, carbon dioxide and temperature,
- safety instructions for emptying the silo,
- safety instructions to protect personnel from the hazards of carbon monoxide and carbon dioxide,

- instructions to restrict the access to areas affected by the fire or its consequences.

The alarm plan should be made accessible at a central location of the plant, for example at the master display.

Especially, the plant operators should be instructed regularly about the contents of the alarm plan and about the appropriate actions to be taken in the case of a fire. In practice, regular exercises where the operating personnel cooperate with the local fire department have been revealed to be of high value as a training for effective fire fighting.

8.3 Measures in Case of Fire

8.3.1 Alerting

Taking into account the preventive measures fixed in the alarm plan, in the case of a fire alarming has to be undertaken as fast as possible. This includes alerting all parties to be involved. Limiting losses in a fire to a minimum can only be achieved by fast alarm and early initiation of fire fighting together with optimum tactics.

8.3.2 General Measures

Fires in silos are connected with several accompanying hazards like subsequent explosions, darting flames and releases of toxic gases. Therefore, it is necessary from the beginning of fire fighting on to take into account tactical and safety measures, like especially

- Restricting the access to a sufficiently large area around the fire site. This should involve the police and prevent trespassing in the hazardous area.
- Restricting the access to rooms or compartments where during inertization the oxygen concentration may fall below 18% of volume fraction or the concentration of carbon monoxide or carbon dioxide exceeds significantly the maximum allowable concentration (MAC, for CO 30 ppm, for CO_2 5000 ppm). These areas have to be cleared from persons before starting inertization and remain closed for the whole procedure. Signs at the access points like doors and so on to these areas have to warn of the hazard.
- Registration of the forces who have to enter restricted areas, for example for rescuing missing persons and so on. Forces who inevitably have to work in such areas have to be registered when entering and again when leaving these areas.
- Areas where the hazard of explosible or toxic atmosphere is expected have to be monitored using appropriate measurement equipment.

- Protective clothing has to match the needs of the expected hazard.
- In areas affected by explosion venting, for example in front of bursting disks or explosion venting panels and so on, no persons are allowed to stay.

8.3.3 Sealing of the Silo

To avoid an undesired entrainment of oxygen into the silo promoting fire propagation, all openings have to be closed, for example by special closings prepared in advance or by foils covered with sand. The latter is often used for horizontal openings on top of the silo.

8.3.4 Inerting and Concentration Measurements

In dependence on the stored material and on the level of filling within the silo, the inert gas has to be injected either from the discharge openings or from the silo top. During injection dispersion of dust has to be avoided in any case. Good experiences have been made using nitrogen as inert gas. In contrast to carbon dioxide, nitrogen is not toxic. Moreover, it is easy to store and to transport or even to produce on site if necessary.

The injection rate depends on the size and the filling level in the silo. It is recommended to reduce the oxygen volume fraction to less than 2%. For ascertaining the success of extinction this level should be kept for several days. In certain circumstances, in addition to the inert gas other extinguishing agents like foam, water spray or special components like Firesorb® should be applied for cooling down the silo.

To avoid explosible atmosphere of dusts during emptying the silo, the oxygen volume fraction should be kept at least below the limiting oxygen concentration of the dust. As a rule of thumb, below an oxygen concentration of 8% the hazard of a dust explosion can be precluded.

Measurement of the oxygen volume fraction within the silo has to be performed continuously to properly control the supply of inert gas. An additional measurement of the concentration of carbon monoxide gives evidence of the intensity of the fire and the efficiency of inerting. An impression of such measurements is given in Figure 8.4.

Measuring concentrations of oxygen, carbon monoxide and carbon dioxide has to be performed also in the immediate vicinity of the silo to note hazardous gas concentrations and to trigger protective measures. For example, for concentrations of CO and CO_2 above the permitted limits breathing apparatus has to be used.

8.3.5 Emptying the Silo

Emptying a silo having been on fire should be started, if feasible, not before all signs of the fire have vanished. Otherwise the following safety precautions have to be considered:

Figure 8.4 Data logging unit for temperature and CO concentration measurements.

- Before emptying the silo the vicinity of the discharge openings has to be cleared of any dusty material.
- Injection of inert gas should be maintained during emptying of the silo. In certain circumstances a previous injection of light foam (to avoid dust dispersion) may be recommendable.

A special problem when emptying a silo is the formation of so-called bridges of bulk material. Such bridges can be formed either by smoldering of the bulk material or by increased moisture due to the adsorption of water used for fire extinction.

Actions to break the bridges or to drill holes into them should only be started after sufficient inerting of the space above and below the bridge. If this is done carelessly, airflow through the fracture in the bridge can ignite the smoldering material.

The most dangerous moment is when the bridge is breaking with setting free of smoldering nests. Since a dispersion of dust cannot be avoided when the bridge collapses, an insufficient inerting with certainty ends in a dust explosion.

The formation of explosible dust–air mixtures has to be avoided also in the space below the silo discharge. Eventually, when the silo is emptied smoldering or glowing material has to be extinguished with water spray or water mist. For materials which are difficult to wet a wetting agent has to be added to the water.

8.4 Summary

It is very likely that fires in silos in the future will be a big challenge for plant operators and fire fighters. Due to the variety of silo constructions, the manifold stored products

and the differences in the infrastructure with respect to fire fighting, a universal recipe for fire protection and fighting cannot be given in practice.

In general, only an integrated concept including preventive measures, adequate construction, processing and plant operation and cooperation with local fire fighters and silo fire experts can guarantee a comprehensive success. Such a concept, however, always makes an individual assessment necessary.

9
Predictive Tools for Hazard Assessment of Self-Ignition

Ulrich Krause

Promoted by the rapid development of computer resources, various problems in fire safety engineering have recently been tackled by application of advanced computer models. This has also been the case for self-ignition and fire propagation during storage of bulk materials; see Krause *et al*. [1].

The general features of such models are

- They are based on physical principles like conservation of mass, momentum and energy.
- These principles are reflected by a set of partial differential equations which in most cases have to be solved numerically, for example by finite difference, finite volume or finite element schemes.
- The set of conservation laws is mathematically closed by so-called constitutive equations which include submodels for chemical reactions, temperature dependence of transport coefficients and others.

In general, numerical simulations of these phenomena offer the following advantages:

- There are no limitations for geometry. Three-dimensional geometries can be treated as well as "sandwich" materials, that is those consisting of different layers each exhibiting its own material properties.
- Any kind of thermal boundary conditions (given surface temperature, given heat flux, Newtonian cooling) can be considered. In addition, the boundary conditions may vary in space and time.
- The dependence of the temperature evolution with time can be treated such that the entire process of heating, self-ignition, runaway and burnout can be followed continuously.
- Information is obtained on local distributions of the chemical species of interest and their evolution with time.
- Kinetic and transport-controlled reaction regimes may be considered, the latter including diffusion and convection of gaseous chemical species.

The input which has to be provided to the model covers

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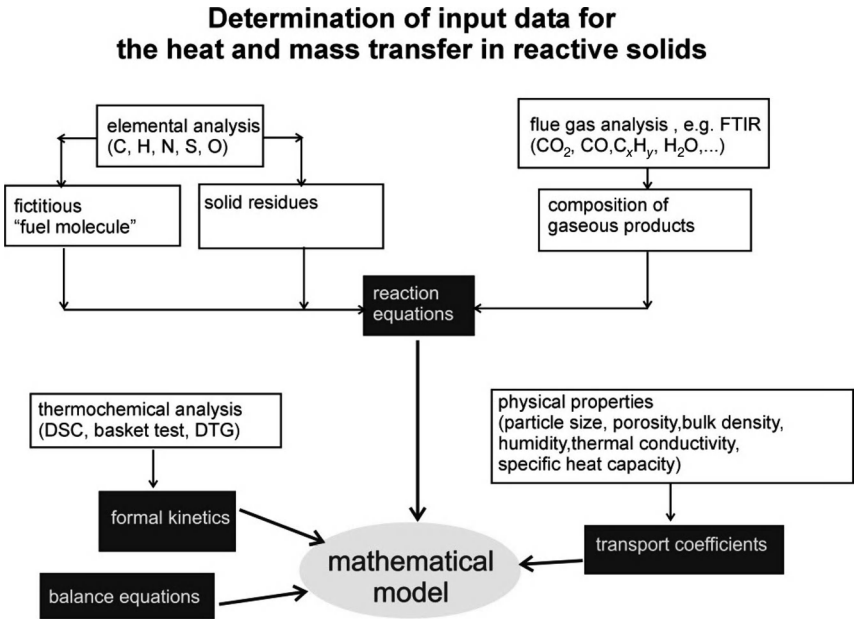

Figure 9.1 Components of a mathematical model for self-ignition and fire propagation in deposits of porous combustible solids.

- the quantities given in Table 9.1,
- boundary and initial conditions,
- geometry data.

It is beyond the scope of the present book to explain all the experimental methods to obtain the quantities contained in Table 9.1 in detail. This has been done, for example, by Lohrer [2].

Figure 9.1 shows how the output of the laboratory tests and the different components of the physical and chemical model are combined to result in a general simulation model. This model allows for computing the evolutions with time of temperature and concentrations of chemical species in an either two- or three-dimensional computational domain.

Based on such a model fire scenarios can be predicted which allow a precise assessment of the hazard of self-ignition and subsequent fire propagation in the real silo. For this kind of problems finite element (FEM) computer codes have been revealed to be most suitable. Creating such a computational process includes the following steps:

- Uploading the geometry data from computer-aided design (CAD). Advanced FEM codes offer interfaces to common CAD programs. Alternatively, the FEM codes offer tools to create the geometry "from scratch."
- Creating a suitable mesh of finite elements. While for simple geometries automated algorithms produce sufficiently accurate meshes, in some cases user-defined modifications to improve the mesh may be necessary.

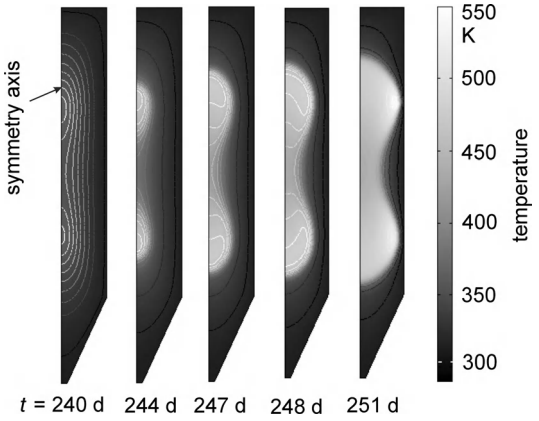

Figure 9.2 Evolution with time of the temperature field during self-ignition and subsequent propagation of smoldering in a silo with permeable walls.

- Setting the boundary and initial conditions for heat and mass transfer.
- Setting the physical properties of the materials within the computational domain.
- Setting the parameters for the numerical solution.
- Executing the computation.

As an example, storage of crushed lignite coal in a silo of 78 m^3 over a period of several months was investigated. Figure 9.2 shows the evolution with time of the temperature within the silo when it was supposed that the silo walls were permeable for air. It can be seen that – as a sufficient amount of oxygen is supplied to the reaction zone – two hot spots are formed and the smoldering fire propagates towards the outer surface of the silo.

In contrast to this, Figure 9.3 shows the temperature evolution with time for the same silo and for the case that the silo walls are not permeable for air and an

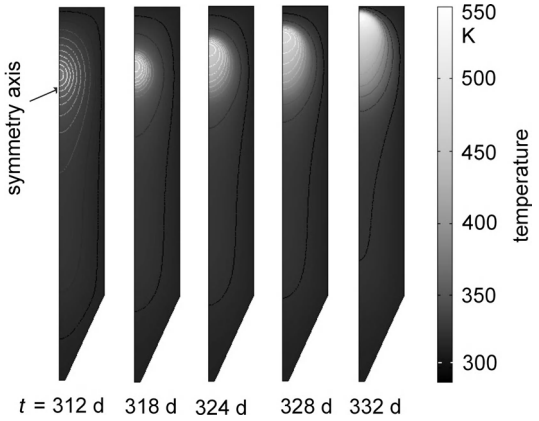

Figure 9.3 Evolution with time of the temperature field during self-ignition and subsequent propagation of smoldering in a silo with non-permeable walls.

entrainment of oxygen is only possible from the silo top and the opening at the bottom of the funnel. In this case only one hot spot is formed and the smoldering front propagates towards the silo top. The propagation velocity is notably smaller than for the case with permeable walls.

This example demonstrates the capabilities of predictive methods to forecast self-ignition and smoldering propagation during storage of flammable bulk materials in silos. Applying this method during a hazard analysis allows us to determine storage conditions which effectively prevent the breakout of a fire.

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